UKRAINIAN JOURNAL OF FOREST AND WOOD SCIENCE

UKRAINIAN JOURNAL OF FOREST AND WOOD SCIENCE

Journal homepage: https://forestscience.com.ua/en
*Ukrainian Journal of Forest and Wood Science*, 15(3)

УДК 630

**Засновник:**
Національний університет біоресурсів і природокористування України,
ТОВ «Наукові журнали»

**Рік заснування: 2010**
Періодичність випуску: 4 рази на рік

*Рекомендовано до друку та поширення*
*через мережу Інтернет Вченою радою*
*Національного університету біоресурсів і природокористування України*
*(протокол № 1 від 15 серпня 2024 р.)*

**Державна реєстрація:**
**Ідентифікатор медіа R30-02293.**
Рішення Національної Ради України
з питань телебачення і радіомовлення
№ 1795, протокол № 31 від 21.12.2023 р.

**Журнал входить до переліку фахових видань України**
Категорія «А». Спеціальності:
206 « Садово-паркове господарство», 205 «Лісове господарство»,
187 «Деревообробні і меблеві технології», 101 «Екологія», 091 «Біологія»
(наказ Міністерства освіти і науки України № 1543 від 20 грудня 2023 року)

**Журнал представлено у міжнародних наукометричних базах даних, репозитаріях та пошукових системах**:
Index Copernicus International, Scopus, Google Scholar, Національна бібліотека України імені В. І. Вернадського, MIAR, BASE, CABI, AGRIS, GEOBASE, Polska Bibliografia Naukowa (PBN), Scientific Indexing Services (SIS), UCSB Library, Ulrichsweb Global Serials Directory, EBSCO, Dimensions, University of Oslo Library, University of Hull Library, SOLO – Search Oxford Libraries Online, European University Institute, Leipzig University Library, Cambridge University Library, ASCI, Zendy, OUCI (Open Ukrainian Citation Index), Worldcat, Scilit

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**UKRAINIAN JOURNAL OF FOREST AND WOOD SCIENCE**

**Journal homepage: https://forestscience.com.ua/en**
***Ukrainian Journal of Forest and Wood Science*, 15(3)**

UDC 630

**Founder:**
National University of Life and Environmental Sciences of Ukraine,
LLC “Scientific Journals”

**Year of foundation: 2010**
Frequency of issue: Four times per year

*Recommended for printing and distribution*
*via the Internet by the Academic Council*
*of National University of Life and Environmental Sciences of Ukraine*
*(Minutes No. 1 of August 15, 2024)*

**State Registration:**
**Media identifier R30-02293.**
Decision of the National Council
of Television and Radio Broadcasting of Ukraine
No. 1795, Minutes No. 31, dated 21.12.2023.

**The journal is included in the list of professional publications of Ukraine**
Category “A”. Specialities:
0812 – Horticulture, 0821 – Forestry, 0722 – Materials (Paper and Wood),
0521 – Environmental Sciences, 0511 – Biology
(Order of the Ministry of Education and Science of Ukraine No. 1543, dated December 20, 2023)

**The journal is presented international scientometric databases, repositories and scientific systems**:
Index Copernicus International, Scopus, Google Scholar, Vernadsky National Library of Ukraine,MIAR, BASE, CABI, AGRIS, GEOBASE, Polska Bibliografia Naukowa (PBN), Scientific Indexing Services (SIS), UCSB Library, Ulrichsweb Global Serials Directory, EBSCO, Dimensions, University of Oslo Library, University of Hull Library, SOLO – Search Oxford Libraries Online, European University Institute, Leipzig University Library, Cambridge University Library, ASCI, Zendy, OUCI (Open Ukrainian Citation Index), Worldcat, Scilit

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Journal homepage: https://forestscience.com.ua/en
*Ukrainian Journal of Forest and Wood Science*, 15(3)

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Received: 10.05.2024; Revised: 01.08.2024; Accepted: 15.08.2024

UKRAINIAN JOURNAL OF FOREST AND WOOD SCIENCE

UKRAINIAN JOURNAL OF FOREST AND WOOD SCIENCE

Journal homepage: https://forestscience.com.ua/en
*Ukrainian Journal of Forest and Wood Science*, 15(3)

UDC 630*228.81
DOI: 10.31548/forest/3.2024.08

# The state and structure of beech primaeval forests in the "Zacharovanyi Krai" National Nature Park

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**Abstract**. The relevance of the study is determined by the need to preserve natural values, which are considered the heritage of all mankind, namely the primaeval forests and old-growth beech forests of the UNESCO World Natural Heritage. The aim of the research was to study the state and structure of the beech primaeval forest in the national nature park "Zacharovanyi Krai". For the study, a permanent sample plot of 1 ha (100×100 m) was laid down in the prevailing forest type – moist pure beech forest. This plot is located in the optimal forest-growing conditions for European beech (*Fagus sylvatica* L.) within the Vyhorlat-Hutyn volcanic ridge of the Ukrainian

***Suggested Citation:***
Shyshkanynets, I., Zadorozhnyy, A., Potish, L., & Mihaly, A. (2024). The state and structure of beech primaeval forests in the "Zacharovanyi Krai" National Nature Park. *Ukrainian Journal of Forest and Wood Science*, 15(3), 8-24. doi: 10.31548/forest/3.2024.08.

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Carpathians. It was found that the beech forest stand on the plot is pure in composition and complex in form, characterised by different development phases (age groups by diameter): the first layer stand belongs to the mature age group (senile), the second layer – to the middle-aged group, and the third – to the pole (virginal). It was determined that 95% of the primaeval forest stock is the stock of the first layer, while the share of commercial trees of the first layer is 89% (66% of the total volume of stem wood of trees on the permanent sample plot). The main types of damage in the site are caused by abiotic factors. As a result of such damage, 43 $m^3 \cdot ha^{-1}$ of deadwood was recorded, characterised by all 5 stages of decomposition. Under the canopy of the stand, 10,375 $pcs \cdot ha^{-1}$ of undergrowth was recorded, of which the share of beech is 88%. Beech undergrowth is weakly differentiated by age groups: it was recorded only in the group of 7-year-olds and older and well-differentiated by height groups. By age group, undergrowth belongs to the juvenile-immature age state. The herbaceous cover is typical for nemoral forests. The presence of stationary research plots in the National Nature Park “Zakharovanyy Kray” makes it possible to constantly monitor the trends of natural development of the ecosystem – the beech primaeval forest

**Keywords**: Ukrainian Carpathians; stand; undergrowth; deadwood; ecosystem

## Introduction

Beech primaeval forests hold multifaceted scientific, natural, ecological, and social significance. However, the increase in human activity and climate change threatens these natural complexes, making research relevant. Understanding the current state of beech primaeval forests enables the development of effective measures for their protection and management, contributing to the preservation of these unique ecosystems for future generations.

According to V.I. Parpan *et al.* (2017), primaeval forests are forest ecosystems (communities) that have arisen and developed naturally under the influence of only natural forces and phenomena and have undergone a complete cycle of development without significant human interference. Their species, age and spatial structure are determined only by factors of the natural environment.

Considering the characteristic cenotic peculiarities of primaeval forests, S. Stoyko (2018) defines them as follows: a primaeval forest is an ecosystem formed during phylocenogenesis, in which all age groups are wrepresented – from juvenile to the disintegration group of the cenosis, the relationships between the autotrophic and heterotrophic blocks and the pedosphere, and therefore it functions as a self-regulating ecosystem.

As of 2020, 97 thousand hectares of primaeval forests, quasi-virgin forests, and natural forests have been identified in Ukraine (Shparyk *et al.*, 2021). According to A. Smaliychuk (2019), at the beginning of 2018, over 94 thousand hectares of primary natural forests were identified in the Ukrainian Carpathians, of which about 53% are classified as primaeval forests. The researcher noted that about half of the identified natural forests in the region have protected status, and the same share belongs to the Emerald Network.

In terms of administrative regions, the largest area of natural forests is found in the Zakarpattia Region, accounting for 71% of their total area (Smaliychuk & Gräbener, 2018). Beech natural forests predominate by main tree species (58%), which in the prevailing forest types (moist pure beech forest – 18%, moist pure sub-beech forest – 18%), mainly form pure beech stands.

Intensification of primaeval forest research began two decades ago, which is obviously associated with the inclusion of Carpathian beech primaeval forests in the list of UNESCO World Natural Heritage sites. At the same time, beech primaeval forests were studied mainly on the territory of the Carpathian Biosphere Reserve (Trotsiuk *et al*., 2012; Kabal *et al*., 2021), in the national nature parks of the Carpathian region and in other protected areas, which led to the proposal to expand the national nature parks. I.F. Shyshkanynets *et al.* (2023) noted that within the territory of the potential expansion of the national nature park "Zacharovanyi Krai", 2,178.5 ha of primaeval forests, 1,197.0 ha of natural forests, 881.2 ha of old-growth forests, and 275.0 ha of primaeval forests were identified. The corresponding sites require effective conservation within the framework of a multifunctional object of the natural reserve fund – the national natural park.

It is also worth noting that research on the territory of the Carpathian Biosphere Reserve is conducted with the support of the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL) and has a systematic character. The corresponding studies are conducted on a 10-hectare plot using a specially developed methodology by B. Commarmot *et al.* (2013). In the rest of the Carpathian region, research on beech primaeval forests mostly does not have a systematic character.

The aim of this work is to study the primaeval beech (*Fagus sylvatica* L.) forest in the territory of the NNP "Zacharovanyi Krai", which is a UNESCO World Natural Heritage site. To achieve this aim, the following main research objectives have been set: to investigate the state, structure, and development dynamics of the beech primaeval forest in the most widespread forest type – moist pure beech forest.

## Materials and Methods

In the National Nature Park (NNP) "Zacharovanyi Krai" (Ukraine, Zakarpattia Region), research on primaeval forests began in 2013: a permanent sample plot (PSP) of 1 hectare (100×100 m) was established, and information about it is provided in the publication by I.F. Shyshkanynets *et al.* (2019). In addition, studies of myxomycetes of beech primaeval forests have been conducted (Dudka & Kryvomaz, 2013).

It is worth noting that on July 7, 2017, two areas (clusters) of the NNP (Irshavka – 93.94 ha and Velykyi Dil – 1,164.16 ha) were included in the list of UNESCO World Natural Heritage sites (Hamor, 2023). The Irshavka cluster consists of primaeval forests of the Pidhirnianske forestry, while the Velyky Dil cluster consists of primaeval forests of the Pidhirnianske forestry (18%), old-growth forests of the Ilnytske forestry (59%), and primaeval forests of the state enterprise (SE) "Dovzhanske Forestry-Hunting Management" (FHM) (23%) (Shyshkanynets *et al.*, 2019). At the same time, the corresponding plots in the SE "Dovzhanske FHM" are agreed upon for inclusion in the NNP. The PSP is located in the Irshavka cluster.

In 2023, trees with a diameter ⩾6 cm were numbered on the PSP and the boundaries of the plot were restored in situ. Tree inventory was carried out using a measuring fork: diameters were measured in 2-centimeter increments at breast height (1.3 m), classified by species. At the same time, technical suitability categories, Kraft classes, and sanitary conditions were assessed (Grom, 2007; Methodical recommendations..., 2011; Sanitary Forests..., 2016). Tree heights and crown lengths were measured using a height measurer Vertex IV (Sweden) on 36 trees: from the middle, upper, and lower levels (12 trees in each layer).

The sanitary condition index was calculated using formula (1):

$$I_c = \frac{1}{N}\sum_{J=1}^{6} K_j \cdot n_j, \qquad (1)$$

where $I_c$ is the sanitary condition index; $K_1 \ldots K_6$ are the tree condition categories; $n_1 \ldots n_2$ are the number of trees in each condition category; $N$ is the total number of trees considered. If $I_c \leqslant 1.5$, the stand is considered healthy; 1.6-2.5 – weakened; 2.4-3.5 – severely weakened; 3.6-4.5 – drying out; ⩾4.6 – dried up.

The Kraft class index was calculated using formula (2):

$$I_K = \sum_{J=1}^{N} K_j \cdot n_j \,/\, \sum_{j=1}^{N} n_j, \qquad (2)$$

where $I_{\kappa}$ is the Kraft class index; $K_1 \ldots K_5$ are the Kraft class categories; $n_1 \ldots n_2$ are the number of trees in each category; $N$ is the total number of trees considered.

To assess defoliation, the atlas of the loss of the assimilation apparatus in forest trees (Borecki & Keczynski, 1992) was used. Based on the defoliation of trees, the average value of the feature was determined for the tree species and stand, and the stand was classified according to damage to one of four degrees: undamaged (0) – defoliation ⩽10%; slightly damaged (1) – 11-25%; moderately damaged (2) – 26-60%; severely damaged (3) – 61-90%; dead (4) – 91-100%.

To determine the stability of the beech forest stand, the stability coefficients (ratio of crown length to tree height) and slenderness (ratio of tree height to its diameter) were also determined (Cherniavskyi, 2006). Additionally, a transect measuring 10×100 m was laid out in situ in the middle of the PSP (along the slope), within which trees were assessed according to the IUFRO (International Union of Forest Research Organizations) classes.

When calculating the Cox clumping index, the transect was first divided into subplots of a fixed size (10×10 m). The index was determined by the formula (3) as the ratio of the variance of the number of trees in the subplots to the average number of trees (Kaganjak & Rehush, 2014):

$$I_c = \frac{\delta^2}{n}, \qquad (3)$$

where $I_c$ is the Cox index; $\delta^2$ is the variance; $n$ is the average number of trees per subplot, pcs. The Cox index can take the following values: $I_c < 1.0$ indicates a uniform distribution of trees; $I_c > 10$ indicates a clumped distribution of trees; $\mathrm{I_c} \approx 1.0$ is characteristic of a random distribution of trees.

The accounting of self-seeding and undergrowth was carried out within the transect. For this purpose, 20 plots of 2×2 m were laid out, evenly spaced from each other (2 within a square of 10×10). Within the plots, natural regeneration was assessed by species, height groups, age, and condition. Age was determined by the number of increments (whorls) in the individual, and condition by the presence of damage. Individuals without signs of damage and with good annual increments were classified as healthy; those with slight annual increments (<5 mm), occasional dry branches, minor mechanical damage to the trunk (bark damage less than 1/4 of the trunk perimeter), and the presence of galls were classified as slightly weakened; individuals with 1/3 of the tree dried (broken) were classified as moderately weakened; those with up to 3/4 of the tree dried (broken), and a trunk tilt greater more than 45° were classified as severely weakened.

The description of the herb cover was carried out by species, assessing the abundance of the species according to the H.M. Vysotsky scale (Methodical recommendations…, 2011). The study was conducted in accordance with the Convention on Biological Diversity (1992) and the Convention on the Trade in Endangered Species of Wild Fauna and Flora (1973). As for deadwood, it was counted during the general inventory of trees on the PSP, classifying it as standing deadwood or damaged, and assessing it according to the five stages of decomposition (Commarmot *et al.*, 2013). Additionally, within the transect, wood residues or branches with a diameter of ⩾7 cm that were not included in the previous inventory were counted

## Results and Discussion

On the territory of the NNP "Zacharovanyi Krai", 300.5 hectares of beech primaeval forests have been identified (Order of the Ministry of Ecology and Natural Resources of Ukraine No. 161, 2018).

The predominant forest type for the growth of primaeval forests is moist pure beech forest ($D_3$-B) – 264.9 ha (D – trophotope, characterising the most fertile soils (habitat conditions); 3 – hygrotope, characterising moist soils; B – beech forest, the predominant (indigenous) species for these habitat conditions) and fresh pure beech forest ($D_2$-B) – 35.6 ha (2 – hygrotope, characterising fresh soils).

The PSP is located in the predominant forest type ($D_3$-B), which makes it possible to monitor the dynamics of development of the beech primaeval forests growing in these conditions. A more detailed silvicultural-taxation characteristic of the beech forest stand (primaeval forest), where the PSP is located, is given in Table 1.

**Table 1.** Silvicultural-taxation characteristics of beech forest stand (primaeval forest) based on forest management materials (2011, 2021 years)

| Forestry | Sq./Species | Area, ha | Stand composition | Age, years | $H_{avg}$, m | $D_{avg}$, cm | Yield class | Forest type | Density | Stock, $m^3 \cdot ha^{-1}$ | Exposure | HASL, m |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Pidhirnianske | 2011 | | | | | | | | | | | |
| | 1/3 | 28.3 | 7Fa.sy.(210)3Fa.sy.(100) | 210<br>100 | 35<br>28 | 56<br>32 | 1 | $D_3$-B | 0.55 | 360 | N, 25° | 800 |
| | 2021 | | | | | | | | | | | |
| | 1/3 | 28.3 | 7Fa.sy.(221)3Fa.sy.(111)+Fa.sy.40 | 221<br>111<br>40 | 35<br>22 | 52<br>24 | 1 | $D_3$-B | 0.65 | 430 | N, 25° | 800 |

**Note:** Fa.sy. – European beech; stand composition – the proportion of the species (genus) in the total stock expressed in tenths of a unit; HASL – height above sea level; $H_{avg.}$ – the average height of the stand; $D_{avg.}$ – the average diameter of the stand

**Source:** developed by the authors

It is worth noting that over a 10-year period, the stand stock per hectare has increased significantly (by 19%): apparently, the data from the 2013 studies were taken into account by the taxator (Table 2). According to the results of the 2013 studies (Table 2), it was found that the beech stand on the PSP is pure in composition and complex form: the middle and lower layers are pronounced. At the same time, the share of stem wood of trees growing in the first layer is dominant, accounting for 92.7% (404 $m^3 \cdot ha^{-1}$).

**Table 2.** Silvicultural-taxation characteristics of beech primaeval forest on the PSP, 2013

| **Stand composition** | **Distribution by levels** | **Species** | **N, $pcs \cdot ha^{-1}$** | **$H_{avg}$, m** | **$D_{avg}$, cm** | **G, $m^2 \cdot ha^{-1}$** | **M, $m^3 \cdot ha^{-1}$** |
|---|---|---|---|---|---|---|---|
| 10 Fa.sy.+Ac. ps. | First | Fa.sy. | 124 | 35.1 | 52.5 | 26.85 | 401 |
| | Second | Fa.sy. | 57 | 21.5 | 22.6 | 2.28 | 23 |
| | Third | Fa.sy. | 267 | 9.7 | 10 | 2.11 | 9 |
| | First | Ac.ps. | 1 | 37.5 | 52.0 | 0.21 | 3 |
| Total living | | | 449 | | | 31.45 | 436 |
| Dead lying | | Fa.sy. | 15 | | 42.5 | 2.13 | 27 |
| Dead standing | | Fa.sy. | 25 | | 44.2 | 3.84 | 49 |
| Total dead | | | 40 | | | 5.97 | 76 |

**Note:** Fa.sy. – European beech, Ac.ps. – sycamore, N – number of trees per 1 hectare; $H_{avg.}$ – the average height of the stand; $D_{avg.}$ – the average diameter of the stand; G – absolute density expressed in square meters per 1 hectare; M – wood stock expressed in cubic meters per 1 hectare

**Source:** developed by the authors

As a result of repeated surveys in 2023 at the PSP, it was found that the total number of trees and the sum of cross-sectional areas decreased by 6 and 3%, respectively (Table 3). At the same time, the stock increased by 10%, which is apparently explained by an increase in the average height of the first layer stand: heights were measured in different trees. It is also worth noting that in a complex beech stand, not all tree tops are well visible, which complicates the process of measuring heights in the same trees.

**Table 3.** Silvicultural-taxation characteristics of beech primaeval forest on the PSP, 2023

| **Stand composition** | **Distribution by levels** | **N, $pcs \cdot ha^{-1}$** | | **$H_{avg}$, m** | **$D_{avg}$, cm** | **G, $m^2 \cdot ha^{-1}$** | **M, $m^3 \cdot ha^{-1}$** | **P (relative)** | **Class of heights** |
|---|---|---|---|---|---|---|---|---|---|
| | | **total** | **Fa.sy.** | | | | | | |
| 10 Fa.sy.+Ac.ps. | First | 137 | 136 | 37.7 | 48.0 | 27.3 | 454.6 | 0.61 | 1a (c) |
| | Second | 79 | 79 | 18.8 | 18.0 | 2.1 | 18.7 | 0.06 | 2 |
| | Third | 207 | 207 | 9.8 | 8.0 | 1.2 | 6.9 | 0.05 | 2 |
| The entire stand | | 423 | 422 | - | - | 30.6 | 480.2 | 0.72 | - |
| *100 largest trees* | | *99* | *98* | *37.8* | *54.0* | *24.4* | *408.4* | *0.55* | *1a* |
| *Standing dead trees (natural mortality)* | | *5* | *5* | *7.0* | *10.0* | *0.1* | *0.3* | *0.00* | *5a* |
| *Standing dead parts of the stem with lying parts of crowns (natural mortality)* | | *7* | *7* | *33.0* | *62.0* | *2.3* | *34.0* | *0.05* | *2* |
| *Dead parts of stems (assortments) and dead lying parts of trees (assortments)* | | - | - | - | - | - | *8.98* | - | - |

**Note:** Fa.sy. – European beech, Ac.ps. – sycamore; N – number of trees per 1 hectare; $H_{avg}$. – the average height of the stand; $D_{avg.}$ – the average diameter of the stand; G – absolute density expressed in square meters per 1 hectare; M – wood stock expressed in cubic meters per 1 hectare; P – relative density; 1a (c), 2, 5a – indicators characterising stands by height and diameter

**Source:** developed by the authors

The share of stem wood of trees growing in the first layer has not changed significantly compared to 2013 and is 95% (454.6 m$^3$·ha$^{-1}$). 90% of the stock of the main layer (408.4 m$^3$·ha$^{-1}$) is the stock of the *100 largest trees*. At the same time, the trees of the first layer belong to the 1a height class. The share of stem wood of trees of the second and third layers is insignificant (5%), and the trees belong to the 2nd height class, which is evident: they grow under the canopy of the main layer.

On the PSP, the largest number of trees was counted in the lowest thickness steps of the third layer (Fig. 1, Table 3). At the same time, according to their technical suitability, the trees belong to the firewood category. There are commercial trees in the second layer, but their share is insignificant (Table 3). It is worth noting that trees with a diameter of ⩾22 cm were classified as commercial (taking into account the presence of assortments of the quality class D, in the diameter group 20-24 cm, for the beech species). The largest number of commercial trees was counted in the first layer, which is 89% of the total number of trees in the layer. At the same time, the stock of commercial trees on the PSP is 317 m$^3$·ha$^{-1}$, or 66% of the total volume of stem wood of trees on the PSP. Moreover, the share of commercial wood of the first layer complies with standards. As for the share of commercial wood in the second layer: it is significantly smaller, which is characteristic of the corresponding stands. This is explained by the following: trees with a diameter of ⩾22 cm were classified as commercial, while trees with a diameter of ⩾6 cm were considered for the inventory.

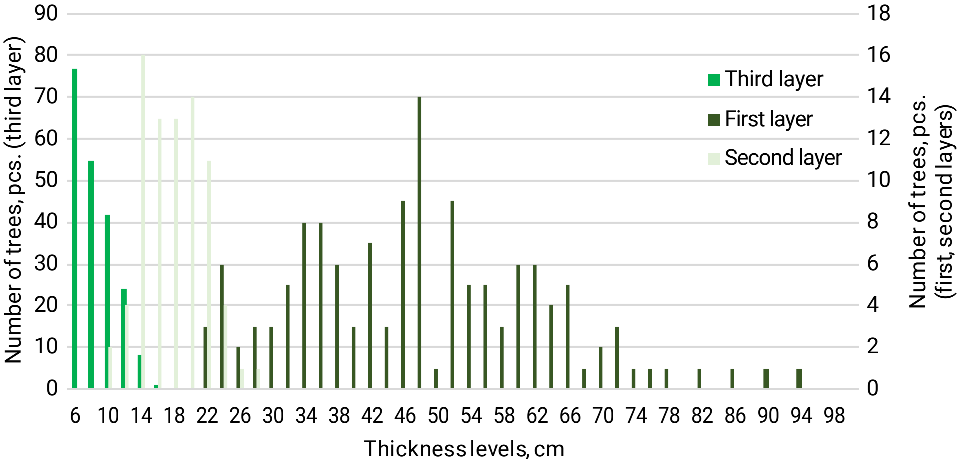

**Figure 1.** Distribution of the number of trees within the layers

**Source:** developed by the authors

Regarding deadwood: on the permanent sample plot, the volume of natural losses amounts to 34.3 m$^3$·ha$^{-1}$. At the same time, the site is dominated by *standing deadwood or damaged (to the point of growth cessation) stem parts with lying crown parts*, the volume of which is 34 m$^3$·ha$^{-1}$ (Table 4). These are mainly trees that have reached the age of physiological maturity and have been damaged by abiotic and biotic factors (windbreak, tinder fungus, etc.). They are characterised by stages 1-4 of deadwood decomposition. The volume of dead stem parts and dead lying parts of trees that are not included in the above list is 9 $m^3 \cdot ha^{-1}$. They are mainly characterised by stages 3-5 of decomposition.

According to the degree of degradation of the photosynthetic apparatus, the beech stand on the PSP belongs to the "slightly damaged" stage (Table 4). At the same time, the loss of leaf mass in the trees of the main layer is somewhat higher than in the trees of the subordinate layer, which is obvious, based on the physiological condition (age) of the stand.

**Table 4.** Indicators of beech stand condition on a permanent sample plot, 2023

| Distribution by layers | Distribution of trees by category of technical suitability | | | | Defoliation index | Kraft class index | Sanitary condition index | Resilience | Slenderness |
|---|---|---|---|---|---|---|---|---|---|
| | commercial, pcs/% | semi-commercial, pcs/% | firewood, pcs/% | standing deadwood, pcs/% | | | | | |
| First | 89<br>61.8 | 29<br>20.1 | 19<br>13.2 | 7<br>4.9 | 22.6 | 2.6 | 1.8 | 0.57 | 0.79 |
| Second | 1<br>1.3 | 13<br>16.3 | 65<br>81.3 | 1<br>1.3 | 14.4 | - | 2.0 | 0.67 | 1.04 |
| Third | - | - | 207<br>98.1 | 4<br>1.9 | 16.5 | - | 2.1 | 0.65 | 1.24 |
| Total | 90 | 42 | 291 | 12 | - | - | - | 0.60 | 0.97 |

**Source:** developed by the authors

The distribution of trees by Kraft classes was carried out for the trees of the first layer. It was found that the Kraft class index is 2.6. The share of trees assigned to the II Kraft class is predominant and comprises 38.0%. The share of trees assigned to the III and IV Kraft classes is smaller and comprises 23.4 and 25.6%, respectively. At the same time, the share of trees assigned to $IV^a$ and $IV^b$ comprised 11.7 and 13.9%, respectively. The smallest share is that of trees assigned to the I Kraft class – 12.4%. The absence of trees assigned to the 5th Kraft class (0.7% of trees are assigned to $V^a$) is explained by the fact that the stand is complex: the remaining trees on the PSP form underlying layers.

According to sanitary conditions, the beech stand is weakened: the sanitary condition index fluctuates within 1.8-2.1, depending on the layer (Table 4). The most damage is observed in the first layer (Table 5). At the same time, the most common damages are cracks – 13.2% (frost cracks – 6.3%), mechanical damage (7.6%) and side-dryness (6.9%). In the second layer, the predominant type is mechanical damage (3.8%). For the third layer, stem (7.1%), windthrow (5.7%) and canker (4.7%). It is worth noting that canker is found only on trees of the third tier. After calculating the stability coefficients, it has been established that the beech primaeval forest on the PSP is resistant to environmental factors: the crown length is 0.57 for trees of the first layer and 0.67 and 0.65 for trees of the second and third layers, respectively (Table 5, Fig. 2).

**Table 5.** Distribution of trees by type of damage on the PSP, 2023

| Distribution by layers | Share of trees by type of damage (%) | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | cracks (including frost cracks) | mechanical damage | side-dryness | ribbed root | hollows | fibre tilt | stem tilt | tinder fungus | growths | windthrow (breakage of top, stem) | stem curvature | cankers | other damages | total |
| First | 13.2 | 7.6 | 6.9 | 5.6 | 4.2 | 4.2 | 4.2 | 4.2 | 4.2 | 3.5 | 2.8 | | 8.2 | 68.8 |
| Second | | 3.75 | 2.5 | | | | 2.5 | | | 1.25 | 1.25 | | 2.5 | 13.75 |
| Third | | 3.3 | 1.9 | | 0.5 | | 7.1 | | | 5.7 | 0.9 | 4.7 | 1.5 | 25.6 |

**Source:** developed by the authors

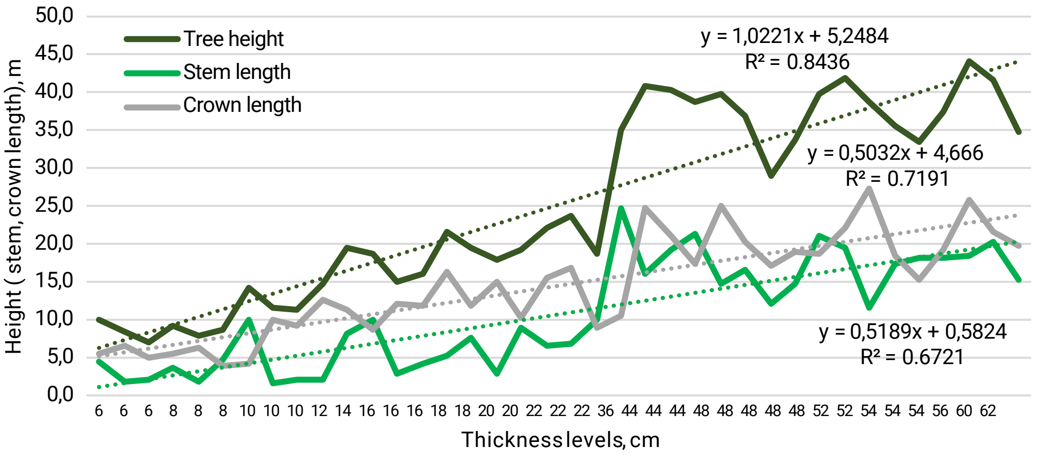

**Figure 2.** Tree heights, lengths of stems and crowns within layers on the PSP
**Source:** developed by the authors

The slenderness coefficient for the first layer is optimal (0.79), for the second layer – limiting (1.04), and for the third – minimal (1.24). The corresponding coefficients confirm that the stand is developing naturally (Cherniavskyi *et al.*, 2006). It is also worth noting that there is a strong correlation between tree diameter and height, and significant correlations between diameter and crown and stem lengths (Fig. 2).

A more detailed study of the beech primaeval forest was conducted on a PSP transect (Table 6). The silvicultural-taxation indicators of the stand on the transect reflect (proportionally) the corresponding indicators of the stand on the PSP, but are slightly lower. Specifically, along the transect, 35 trees were recorded, which constitutes 8.3% of the total number of trees on the PSP; the stock volume is 26.5 $m^3 \cdot ha^{-1}$, accounting for 5.5% of the stock on the PSP. Moreover, the distribution of trees along the transect is uniform.

Regarding the comprehensive stability of the beech stand (IUFRO classes): along the transect, there are predominantly middle-layer trees that are well-developed (with good vitality), of average increment (mostly co-dominant), valuable, with good stems and long crowns (Table 7).

**Table 6.** Silvicultural-taxation characteristics of beech primaeval forest on the transect, type of tree placement

| Stand composition | Distribution by levels | N, $pcs \cdot ha^{-1}$ | $H_{avg}$, m | $D_{avg}$, cm | G, $m^2 \cdot ha^{-1}$ | M, $m^3 \cdot ha^{-1}$ | Cox index | Type of tree placement |
|---|---|---|---|---|---|---|---|---|
| 10Fa.sy. | First | 7 | 37.7 | 50.0 | 1.4 | 23.9 | 0.65 | uniform |
| | Second | 8 | 18.8 | 18.0 | 0.2 | 2.0 | | |
| | Third | 20 | 9.8 | 8.0 | 0.1 | 0.6 | | |
| The total stand | | 35 | - | - | 1.7 | 26.5 | | |

**Note:** Fa.sy. –European beech; N – number of trees per 1 hectare; $H_{avg.}$ – the average height of the stand; $D_{avg.}$ – the average diameter of the stand; G – absolute density expressed in square meters per 1 hectare; M – wood stock expressed in cubic meters per 1 hectare

**Source:** developed by the authors

**Table 7.** Distribution of beech trees by IUFRO classes along the transect

| Layer | Vitality | Position | Silvicultural value | Merchantability | Crown length |
|---|---|---|---|---|---|
| 2.3 | 1.8 | 2.4 | 4.7 | 5.5 | 4.3 |

**Source:** developed by the authors

After counting the undergrowth, it was found that beech undergrowth is mainly found under the canopy of the mother stand, which is poorly differentiated by age groups: it belongs to the 7-year-old group and older (88.0%). The undergrowth is well differentiated by height groups: its largest number is in the 26-50 cm height group – 33.7% and the lowest is in the height group up to 25 cm – 4.8% (Table 8). In other height groups, the number of undergrowth ranges from 10.8 to 21.7%. The share of sycamore (*Acer pseudoplatanus* L.) undergrowth is insignificant and is 11.0%.

Regarding the condition of the undergrowth, the proportion of individuals categorised as healthy and insignificantly weakened predominates, comprising 44.6% and 45.8% respectively. The shares of individuals categorised as moderately and severely weakened are insignificant, each accounting for 4.8%.

**Table 8.** Distribution of the number of undergrowth within the transect

| **Species** | **Number of undergrowth by age and height groups (cm), pcs.·ha$^{-1}$/%** | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **1-year-old** | **2-3 y.o** | **4-7 y.o.** | **over 7 y.o.** | **Total** | **⩽25** | **26-50** | **51-100** | **101-150** | **151-250** | **⩾250** | **Total** |
| Fa.sy. | | | | 9,125<br>88.0 | **9,125<br>88.0** | 250<br>2.4 | 2,750<br>26.5 | 1,625<br>15.7 | 1,250<br>12.1 | 2,250<br>21.7 | 1,000<br>9.6 | **9,125<br>88.0** |
| Ac.ps. | 125<br>1.2 | | | 1,000<br>9.6 | **1,125<br>10.8** | 250<br>2.4 | 750<br>7.2 | | | | 125<br>1.2 | **1,125<br>10.8** |
| Co.av. | | | | 125<br>1.2 | **125<br>1.2** | | | 125<br>1.2 | | | | **125<br>1.2** |
| Total | 125<br>1.2 | | | 10,250<br>98.8 | **10,375<br>100.0** | 500<br>4.8 | 3,500<br>33.7 | 1,750<br>16.9 | 1,250<br>12.1 | 2,250<br>21.7 | 1,125<br>10.8 | **10,375<br>100.0** |

**Note:** Fa.sy. – European beech; Ac.ps. – sycamore; Co.av. – common hazel

**Source:** developed by the authors

In addition to the above species, spruce (*Picea abies* L.) undergrowth is also found within the PSP. His species appeared in the area due to the arrival of seeds from an adjacent area where a derivative spruce plantation is growing. The undergrowth on the PSP is almost absent: *Sorbus aucuparia* L. and *Corylus avellana* L. are occasionally found. The herbaceous cover is typical for the corresponding forest stand: *Galium odoratum* (L.) Scop. – 2, *Rubus hirtus* Waldst. et Kit. – 1, *Gymnocarpium dryopteris* L.) Newm. – p, *Athyrium filix-femina* (L.) Roth – p, *Dryopteris filix-mas* (L.) Schott – p, *Dentaria glandulosa* Waldst.et Kit. – n, *Oxalis acetosella* L. – u. In the place where surface water comes to the surface, the herbaceous cover is more diverse (about 0.05 ha), in addition to the above species, there are: *Impatiens noli-tangere* L. – 3, *Urtica dioica* L. – 2, *Symphytum cordatum* Waldst. et Kit. ex Willd. – p, *Chrysosplenium alternifolium* L. – p, *Lamium maculatum* L. – n, *Myosotis sylvatica* Ehrh. ex Hoffm. – u. Summer aspect: 15.06-17.08. *Fagetum asperulosum*. The area features an outcrop of rocky formations on the surface. Type of growing conditions: $D^{4C}_{3}$ (wet fairly fertile forest site conditions subtype of the moist fairly site condition).

The study of primaeval forests in the Ukrainian Carpathians, particularly in Zakarpattia, began in the 1930s by the Czech researcher A. Zlatnik in 1938 (Stoyko, 2013). The further history of primaeval forest research within the Ukrainian Carpathians is covered in the studies of U. Brändli & J. Dowhanytsch (2003), F. Hamor & P. Veen (2008). According to forest management zoning ning (Holubets, 2003), the research on the PSP concerns the Volcanic Carpathians (Vyhorlat-Hutyn ridge) and intermountain depressions. The vast majority of research on beech primaeval forests in the Ukrainian Carpathians relates to the Mountain Carpathian forestry district. Thus, P.M. Ustymenko & D.V. Dubyna (2014) established that about 3,000.0 hectares of beech forests on the territory of the Synevyr National Nature Park have the characteristics of primaeval forests. The researchers conducted geobotanical descriptions on the corresponding sites. The research of M.V. Sayats (2009) is dedicated to the beech primaeval forests of the Uzhansky National Natural Park, whose territory is an integral part of the “Eastern Carpathians” international biosphere reserve. It is worth noting that virgin forests are preserved in the

Uzhanskyi National Nature Park, and reserves of beech and beech-spruce forests were created in 1908-1913 (Stoyko, 2018). Repeated studies by Z. Hruby (1997) of the cenotic and age structure of this primaeval forest, on the experimental plots of A. Zlatnik showed that the stock has not changed significantly (Sayats, 2009).

More long-term studies by Yu. Shparyk *et al.* (2018), and V. Trotsiuk *et al*. (2012), which cover the issues of the state and structure of beech primaeval forests, were conducted on the territory of the Carpathian Biosphere Reserve. The authors considered how the diversity of climatic conditions, soil types and relief influence the formation and development of these unique ecosystems. Studying these influences helps to better understand the processes taking place in beech primaeval forests and contributes to their effective management and preservation.

The authors of this study note that even though the above studies were conducted in different institutions and forestry (forest-growing) districts, they were carried out in homogeneous growing conditions (forest type $D_3$-B) and in the alti altitude range, which is optimal for the growth of beech forests. The stands are homogeneous in terms of the composition of the stand, however, there is a difference in the wood stock: in the Carpathian Biosphere Reserve, the stock is higher, which is evidently due to the greater participation of species in the stand composition and the phase (interval of beech tree diameters on the permanent sample plot) of the beech primaeval forest's development (Yanovska, 2015). In particular, the first layer stand belongs to the overmature (post-senile) age group. In the NNP, the interval of diameters of beech trees on the site is smaller, and the stands are also characterised by different phases of development (age groups by diameters): the stand of the first layer belongs to the mature age group (senile), the second layer to the middle-aged group, and the third layer to the pole (virginal) group.

An important structural feature of primaeval forests is also that the first layer of the primaeval forest is the main biogeocenotic horizon, which holds the majority of the forest's wood stock: in the NNP, the corresponding share was 92.7% in 2013 and 95% in 2023. On the PSP in the Carpathian Biosphere Reserve, the corresponding share is identical (about 93%).

The hypothesis that the primaeval forest is a stable ecological system is confirmed by the stability and slenderness coefficients of the stand. At the same time, the prevailing types of damage on the site are cracks, mechanical damage, and side dryness – damage caused mainly by abiotic factors. However, their share is not significant, which is reflected in the commercial structure of the stand: in the first layer, the share of commercial trees is 89% or 66% of the total volume of stem wood of trees on the PSP.

The resilience of this ecosystem to the influence of abiotic factors is confirmed by research on the territory of the Carpathian Biosphere Reserve. Thus, according to Yu.S. Shparyk *et al.* (2018), a windfall in 2007, from which more than 25% of trees were lost in individual thickness steps, did not destroy the primaeval forest – within three years after the disaster, the fullness of the stand was restored, and the decrease in wood stock did not exceed 10%. M.V. Kabal *et al.* (2021) note that at the research station, where more than 80% of the trees were felled by a catastrophic storm after 12 years sufficient natural renewal and the formation of a young forest were found – which indicates a tendency to recover. As a result of the functioning of the ecosystem, it is characterised by different stages of development, including decay: on the plot, were recorded about 43 $m^3 \cdot ha^{-1}$ of deadwood, characterised by five stages of decomposition. *Dry standing or damaged (to the point of stopping growth) parts of the stems with lying parts of the crown* (34 $m^3 \cdot ha^{-1}$) predominate. Long-term studies have established that the amount of dead wood can vary significantly, depending on natural factors, including the aforementioned windfalls.

An important component of the primaeval forest is also its “potential” (undergrowth) – a sufficient number of tree species that can potentially fully replace the maternal stand. During the study, 10,375 pcs·ha$^{-1}$ of undergrowth were recorded, of which beech accounts for 88.0% (Table 7). Beech undergrowth is weakly differentiated by age groups: only in the group of 7-year-olds and older was recorded and well-differentiated by height groups. The absence of undergrowth in younger age groups is explained by the biology of the tree species: fruiting intervals (average yields are observed every 1(4)-6 years) and canopy closure (due to insufficient light, a significant amount of self-seeding dies in the first year of life). However, this amount of undergrowth is optimal for these conditions and the natural development of the ecosystem (phase of development). According to Yu.S. Shparyk & I.M. Yanovska (2017), about 26,000 pcs·ha$^{-1}$ of undergrowth were recorded in a monodominant beech primaeval forest under the conditions of a moist pure beech forest. The larger amount of undergrowth is explained, obviously, by the age of the maternal stand (belongs to the post-senile age group) and the participation of other species in the composition of the maternal stand. In particular, the researchers recorded a significant number of other species in the undergrowth. V. Lavnyy *et al.* (2021) note that natural regeneration of tree species is well formed in the “gaps” of the forest canopy in beech primaeval forests. At the same time, its quantity increases with the increasing size of the gaps in the canopy.

Under the canopy of the monodominant beech primaeval forest, the herbaceous cover is typical for nemoral forests. Moreover, the same vegetation is also found at the research station in the Carpathian Biosphere Reserve.

## Conclusions

The state, structure, and dynamics of development of a beech primaeval forest in the conditions of a moist pure beech forest were studied. It was established that the stand of the first layer belongs to the mature age group (senile), the second layer to the middle-aged group, and the third to the pole stage (virginal). It was determined that 95% o of the primaeval forest’s stock is from the first layer, while the share of commercial trees of the first layer is 89% (66% of the total volume of stem wood of trees on the PSP). The main types of damage on the site are damage caused by abiotic factors. As a result of the corresponding damage, about 43 m$^{3}$·ha$^{-1}$ of deadwood was recorded, which has all 5 stages of decomposition.

Under the canopy of the maternal stand, 10,375 pcs·ha$^{-1}$ of undergrowth were recorded, of which beech accounts for 88.0%. Beech undergrowth is weakly differentiated by age groups: only in the group of 7-year-olds and older was recorded and well-differentiated by height groups. By age group, the undergrowth belongs to the juvenile-immature age state.

The beech primaeval forest in the corresponding growing conditions develops naturally, under the influence of only natural forces and phenomena, without significant human intervention, and its species, age, and spatial structure are determined by environmental factors.

Further research on the state and structure of beech primaeval forests may include a more detailed study of the dynamics of changes in the composition and functioning of the ecosystem over time, as well as an analysis of the impact of various factors, including anthropogenic and climatic, on its stability and self-renewal ability. Additional research may also focus on assessing the vulnerability of these ecosystems to environmental changes and developing adaptation strategies to the future challenges they face. Furthermore, it is possible to conduct research aimed at understanding the relationships between beech primaeval forests and other types of ecosystems in the park in order to ensure a comprehensive approach to their conservation and management.

## Acknowledgements

The authors of the article express their sincere gratitude to the staff of the "Zacharovanyi Krai" National Nature Park for their assistance in conducting field research.

## Conflict of Interest

None.

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# Стан і структура букових пралісів у національному природному парку «Зачарований край»

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**Анотація**. Актуальність дослідження визначається необхідністю збереження природних цінностей, які вважаються надбанням усього людства, – пралісів і старовікових букових лісів Всесвітньої природної спадщини ЮНЕСКО. Метою роботи було дослідити стан та структуру букового пралісу національного природного парку «Зачарований край». Для дослідження закладено постійну пробну площу розміром 1 га (100×100 м) в переважаючому типі лісу – вологій чистій бучині. Дана ділянка розташована в оптимальних для бука лісового (*Fagus sylvatica* L.) лісорослинних умовах, у межах Вигорлат-Гутинської вулканічної гряди Українських Карпат. Встановлено, що буковий лісостан на ділянці є чистим за складом та складним за формою, якому притаманні різні фази розвитку (вікові групи за діаметрами): деревостан першого ярусу належить до стиглої вікової групи (сенільної), другого ярусу – до середньовікової, а третього – до жердняку (віргінільної). Визначено, що 95 % запасу пралісу – це запас першого ярусу, при цьому частка ділових дерев першого ярусу становить 89 %

(66 % від загального об'єму стовбурної деревини дерев на постійній пробній площі). Основними видами пошкоджень на ділянці є пошкодження спричинені абіотичними чинниками. У результаті відповідних пошкоджень, обліковано 43м$^3$· га$^{-1}$ мертвої деревини, якій притаманні всі 5 стадій розкладу. Під наметом деревостану обліковано 10375 шт·га$^{-1}$ підросту, частка бука у складі якого становить 88 %. Підріст бука слабо диференційований за віковими групами: обліковано лише у групі 7-річного віку і старше та добре диференційований за висотними групами. За віковою групою підріст належить до ювенільно-іматурного вікового стану. Трав'яне вкриття є типовим для неморальних лісів. Наявність стаціонарних ділянок досліджень у національному природному парку «Зачарований край» дає можливість постійно відстежувати тенденції природного розвитку екосистеми – букового пралісу

**Ключові слова**: Українські Карпати; деревостан; підріст; мертва деревина; екосистема

Received: 19.04.2024; Revised: 26.07.2024; Accepted: 15.08.2024

UKRAINIAN JOURNAL OF FOREST AND WOOD SCIENCE

Journal homepage: https://forestscience.com.ua/en
*Ukrainian Journal of Forest and Wood Science*, 15(3)

UDC 630.4:574
DOI: 10.31548/forest/3.2024.25

# Use of environmental indicators to assess the state of forest ecosystems

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**Abstract**. The purpose of the study was to comprehensively analyse the effectiveness of environmental indicators in determining the state of forest ecosystems and their ability to reflect changes in the ecological balance. During the study, the influence of anthropogenic factors on biomass, soil acidity, and species diversity of forest ecosystems in the Sumy Oblast of Ukraine

***Suggested Citation:***
Skliar, V., Skliar, Yu., Sherstiuk, M., Smoliar, N., & Kanivets, O. (2024). Use of environmental indicators to assess the state of forest ecosystems. *Ukrainian Journal of Forest and Wood Science*, 15(3), 25-42. doi: 10.31548/forest/3.2024.25.

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was evaluated. Field studies were conducted to determine the soil acidity, the biomass of plants and animals in anthropogenic and natural forest areas, followed by statistical analysis of the data. The degree of degradation of forest areas as a result of human activity was determined and the environmental consequences of these changes for natural systems were evaluated. The results showed that anthropogenically modified areas have reduced biomass (100 t/ha) and species diversity (20 plant species), increased soil acidity (pH 6.5-7) and high concentrations of nitrates and phosphates, compared to mixed forests, where biomass reaches 200 t/ha, species diversity – 50 species of flora, and soil acidity varies from moderately acidic to neutral (pH 5.5-6). These data confirmed the negative impact of human activity on ecosystems, in particular on biomass and soil acidity. It was established that environmental indicators allow forming a comprehensive picture of the state of ecosystems, which is necessary for making informed management decisions aimed at preserving and restoring ecosystems, and at effective management of natural resources. The results obtained demonstrated serious environmental problems as a result of anthropogenic impact on forest ecosystems. A decrease in biomass and species diversity, and an increase in soil acidity in anthropogenic zones indicate the need for urgent implementation of measures for the conservation and restoration of natural forests. The study will be useful in the context of long-term monitoring of ecosystems, which would allow a more detailed investigation of the dynamics of their changes

**Keywords**: bioindicators; biodiversity; sustainable development; environmental monitoring; natural environment

## Introduction

Forest ecosystems perform critical ecological functions that are fundamental to maintaining the health of the planet. These functions include maintaining biodiversity, which ensures the existence of various plant and animal species, regulating the water cycle that affects climatic conditions, and preserving soil resources that are important for agriculture and food security. However, anthropogenic impacts, including deforestation, pollution and climate change, pose significant threats to the health and functioning of these ecosystems. Determining the state of forest systems is a complex task that requires an integrated approach, because it is associated with a variety of factors that affect them, such as changes in the species composition of flora, soil degradation, and socio-economic factors that can affect the management of forest resources. It is important to conduct regular monitoring and assessment of the state of forest ecosystems to timely detect negative changes and take appropriate measures for their conservation and restoration.

Modern research actively highlights the use of various environmental indicators for monitoring the state of the environment. F. Pendrill *et al.* (2019) investigated the role of various environmental indicators in monitoring forest ecosystems in the context of climate change. They focus on integrating vegetation biomass and soil quality data for a comprehensive ecosystem assessment, so their study highlights the importance of a multi-factor approach to more accurately assess the impact of climate change on forest ecosystems. R. Pilli & A. Pase (2018), A.M.I. Kallio (2024) focus on methods for measuring biodiversity as indicators of environmental change in forests. They compare different approaches to assessing species diversity, noting the advantages and disadvantages of each method, which helps to determine the most effective tools for monitoring forest ecosystems.

A. Koshel *et al.* (2024) and S. Hirahara (2020) offered new methods for assessing the state of forest ecosystems, in particular, by analysing soil and water pollution levels. The studies by these researchers demonstrate how these indicators can be used to identify problem areas and predict environmental changes. R. Haines-Young & M. Potschin (2017) examined the role of environmental indicators in territory planning and forest management. Their study emphasised the importance of integrating environmental data into management strategies to preserve ecosystems and improve their sustainability. N. Tsehelnyk (2021) analysed environmental indicators in the context of regional ecosystems, this study highlighted the importance of local factors in monitoring and managing forest ecosystems, and the role of national and international standards. S. Liu *et al.* (2023) and S. Huang *et al.* (2011) focused on the use of remote sensing to assess the state of forest ecosystems. Their results show how the latest technologies can be used to collect data on environmental indicators, which allows for more efficient resource management. I. Hartmane *et al.* (2024) examined the application of environmental indicators to assess the health of forest ecosystems under variable environmental conditions. Their study examined various approaches to collecting and integrating them to assess the overall state of ecosystems.

The conclusions of these studies indicate significant progress in the development and application of environmental indicators for monitoring forest ecosystems. Despite this, many of these studies do not comprehensively cover the relationship between different environmental indicators and their ability to reflect dynamic changes in ecosystems. Existing research mainly focuses on individual aspects, such as air or water pollution levels and species diversity, without properly integrating these data into an overall assessment of the state of ecosystems. This leads to a lack of understanding of how these indicators interact with each other and how their changes can affect overall environmental stability. It is important to pay attention to the need to develop integrated models that consider not only individual indicators, but also their interaction, to provide a more accurate and comprehensive assessment of the environmental state. Such approaches can contribute to better management of natural resources and conservation of biodiversity, because only through systematic analysis can key factors affecting the health of ecosystems be identified. In this context, there is an urgent need for a comprehensive study that will help to better understand the effectiveness and accuracy of environmental indicators for a comprehensive assessment of forest ecosystems. This research is important because forest ecosystems perform critical functions such as maintaining biodiversity, regulating climate, and providing ecosystem services that directly affect human well-being. The problematic issue of this study is to determine which environmental indicators most adequately reflect changes in the state of forest ecosystems in the context of various anthropogenic impacts, such as deforestation, pollution, and climate change.

The purpose of the study is a detailed analysis of the effectiveness of various environmental indicators in determining the state of forest ecosystems, and an assessment of their ability to provide reliable data for making informed management decisions.

## Materials and Methods

The study was conducted from July 2023 to June 2024 in the forest ecosystems of the Sumy Oblast, Ukraine. The study covered three sites in different types of forest ecosystems within the Sumy geobotanic district, in particular: mixed forests, coniferous forests, and areas affected by anthropogenic impact. Throughout the year, research was conducted to assess seasonal fluctuations in environmental indicators and their changes due to various factors. Various types of forest plots were selected to ensure representativeness, including natural and anthropogenic areas. The sample included vegetation, soil, and water samples.

Vegetation species diversity was determined by detailed identification of plants in samples that were collected at each individual site. This process included not only a description of the flora found at these sites, but also a systematic count of the number of species, which allows for a more in-depth analysis of the ecosystem. The study also considered various factors, such as environmental conditions, soil types, and climatic conditions that can affect plant distribution and growth, so the results contribute to a better understanding of the region's biodiversity and its ecological relationships.

Standard instruments for field measurements and laboratory materials for analysis were used. To collect data on vegetation biomass and species diversity, calipers were used to measure tree diameter, squares to assess vegetation cover, and trimmers to take plant samples. Chemical analyses of soil and water were performed using spectrophotometers (model UV-1800, Shimadzu, Japan) to determine the level of pollutants, pH meters (model pH 3110, Wissenschaftlich-Technische Werkstätten, Germany) to assess acidity, and scales (ExplorerEX2202, Ohaus, USA) to accurately measure samples. Aerial photography was used to assess changes in the landscape and biomass (drone – DJI Phantom 4 RTK, DJI, China).

For contextual comparison, archival data on forest ecosystems of Sumy Oblast and regulatory documents on the management of forest resources in Ukraine were used, namely: Forest Code of Ukraine (1994) – the main regulation of relations in the field of forest protection, use, and reproduction. The Law of Ukraine No. 1264-XII "On Environmental Protection" (1991) – defines the general principles of environmental protection, including forest resources. The Law of Ukraine No. 2456-XII "On the Nature Reserve Fund of Ukraine" (1992) – regulates the creation, organisation and protection of territories and objects of the nature reserve fund, which include forest ecosystems. The Law of Ukraine No. 1862-IV "On Ecological Audit" (2004) – establishes the legal basis for ecological audit, which includes an assessment of the ecological state of forest resources. Resolution of the Cabinet of Ministers of Ukraine No. 521-2014-p "On Approval of the Regulation on State Control in the Field of Forestry" (2014) – regulates state control over the use and protection of forest resources.

The pilot study followed institutional, national and international guidelines. The authors of the study followed the standards of Convention on Biological Diversity (1992) and Convention on International Trade in Endangered Species of Wild Fauna and Flora (1979).

## Results

Analysis of environmental indicators in different types of forests is a key to understanding their resilience and adaptive capabilities in response to changing environmental conditions. For mixed forests that include both coniferous and deciduous species, it is important to assess their biodiversity and ecological functions that determine their ability to regenerate and maintain resilience. Coniferous forests, due to their specific flora and fauna, have unique needs that require a separate approach to monitoring the impact of anthropogenic changes (The Law of Ukraine No. 1862-IV, 2004). On the other hand, anthropogenic sites often lose some of their natural function, which requires special measures to restore ecological balance. After conducting an experiment, the following results were obtained. The average vegetation biomass in mixed forests was 200 t/ha, which indicates significant ecosystem productivity. This result is closely related to the large species diversity, which includes numerous species of trees, shrubs, and herbaceous plants. It is important to note that mixed forests are characterised not only by a variety of species, but also by a high density of vegetation, which creates optimal conditions for the development of various organisms. Such ecosystems play a critical role in maintaining ecological balance, as they provide habitat for many animal species, including birds, mammals, and invertebrates. The conservation and protection of such forests is extremely important for the conservation of biodiversity, as they serve as a food source and shelter for many living things. Mixed forests contribute to climate regulation by preserving carbon and reducing the negative impact of climate change.

The average biomass in coniferous forests was 160 t/ha, i.e., a decrease in biomass, which can be explained by the relatively low diversity of vegetation species, and a limited amount of undergrowth. This phenomenon is conditioned by the specifics of the ecological conditions that form coniferous forests. Usually, such forests are characterised by a more uniform vegetation structure, which leads to the fact that the undergrowth, which includes young trees, shrubs, and herbaceous plants, often does not develop properly. The lack of developed undergrowth negatively affects the total amount of biomass in these ecosystems, as the undergrowth performs important ecological functions, such as providing an environment for many animal and plant species, and maintaining soil structure. Thus, to maintain the health and sustainability of coniferous forests, it is important to consider the conservation of species diversity and undergrowth development. Preserving species diversity not only contributes to environmental sustainability, but also provides a balance in the ecosystem that allows it to adapt to climate change and other environmental challenges. Undergrowth development can be achieved through active conservation measures, such as planting new plants, controlling pests and diseases, and managing forest resources, which will create more favourable conditions for the growth and development of various types of vegetation.

The average biomass in anthropogenically modified areas was 100 t/ha. In these areas, a significant decrease in biomass was observed, which was a consequence of the active use of land resources and changes in natural conditions that significantly affected ecosystems. This decline in biomass can be caused by a number of factors, including intensive agriculture, which involves excessive use of chemical fertilisers and pesticides, urbanisation, which leads to the destruction of natural habitats, and climate change, which causes extreme weather events and disrupts the usual ecological balance. Such processes lead to the degradation of natural habitats, a decrease in the diversity of flora and fauna, and to a decrease in soil productivity, which has serious consequences for agriculture and food security. It is important to take urgent measures to restore these areas, in particular through the introduction of sustainable farming practices, the conservation of natural resources, and the creation of protected areas that will not only contribute to the conservation of biodiversity, but also ensure environmental sustainability for future generations, allowing them to enjoy the richness of nature that is available today. To summarise, it is worth adding that mixed forests have the highest biomass, as shown in Figure 1, due to their large species diversity and dense vegetation, which contributes to high ecosystem productivity. Coniferous forests have less biomass due to the uniformity of vegetation and poor undergrowth. Anthropogenically modified areas have the lowest biomass due to active land use and ecosystem degradation. It is important to take measures to restore such areas and preserve the natural balance.

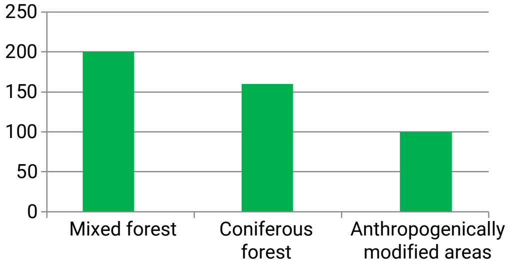

**Figure 1.** Distribution of vegetation biomass in different types of forests, t/ha

**Source:** developed by the authors based on Forest Code of Ukraine (1994)

Based on the results of the analysis of the species diversity of vegetation, the following data were obtained: mixed forest – 50 plant species were identified, which indicates a high species diversity and richness of the flora of this region. This is evidence of ecological stability and ecosystem health, as species diversity is an important indicator of biological activity and adaptive capacity of nature. The mixed forest in which these species have been recorded is characterised by a variety of both woody and herbaceous plants, which creates unique conditions for the development of many animal and plant species, and provides important ecological functions such as air purification, water conservation and soil fertility support. During the study of coniferous forest, 35 plant species were identified, which indicates an average level of flora diversity in this region. Coniferous forests, which occupy a significant part of the territory, are characterised by a smaller number of plant species compared to other types of forests. This is conditioned by the fact that coniferous forests mainly consist of coniferous trees, such as pines, firs and firs, which create special conditions for the growth of other plants. As a result, the undergrowth in such forests is less developed, which limits the opportunities for the development of broad-leaved plants and herbaceous species, so the ecosystem of coniferous forests is more homogeneous, which affects the overall biodiversity of these territories. As a result of the conducted studies, 20 different plant species were identified in anthropogenically modified areas, which indicates a low level of biodiversity in these ecosystems. However, a significant decrease in species diversity in these areas is caused by many factors related to human activity, including urbanisation, agricultural expansion, and environmental pollution, which lead to reduction in flora. As a result, not only the number of species decreases, but also the sustainability of ecosystems, which can have negative consequences for the ecological balance and environmental health. Figure 2 shows the number of plant species in each type of forest.

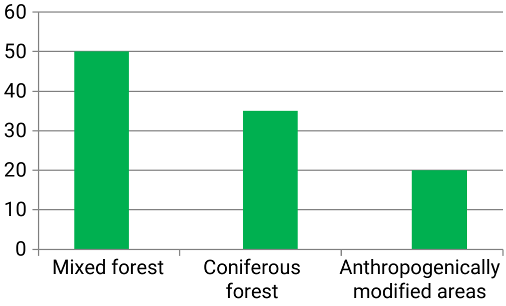

**Figure 2.** Distribution of species diversity in different types of forests, number of plants species

**Source:** developed by the authors based on Forest Code of Ukraine (1994)

Soil acidity was assessed using pH meters, which made it possible to obtain accurate data on the level of acidity in different areas. The results showed that in mixed forest, the pH of the soil ranges from 5.5 to 6, which indicates a moderately acidic reaction. This level of acidity is optimal for the growth and development of many plant species, as it promotes better absorption of nutrients. Moderately acidic soil provides a balance between the availability of trace elements, such as iron and manganese, and prevents excessive activity of toxic elements, so this pH level creates favourable conditions for various plant species, which allows them to develop effectively and ensure high yields. In coniferous forests, the pH of the soil, which ranges from 4.5 to 5, indicates an acidic environment that can have a significant impact on the ecosystem. In such conditions, specific conditions for plant growth are created, since many plant species prefer acidic soils. Coniferous forests, which are usually characterised by a high level of soil acidity, create special ecological niches that affect the species diversity of the undergrowth. This environment promotes the development of certain plant species that can adapt to such conditions, and also limits the distribution of other species that require less acidic soils, so soil acidity is an important factor determining the ecological structure and biodiversity of coniferous forests. The anthropogenically modified areas had a soil pH ranging from 6.5 to 7, which is considered neutral to alkaline, which is optimal for most crops. Neutral acidity in these areas can be a consequence of the use of fertilisers that contain a variety of macro- and microelements necessary for plant growth. In addition, anthropogenic factors, such as changes in land cultivation methods, the use of agrochemicals, and the impact of agricultural activities, can significantly affect the chemical composition of the soil, highlighting the importance of monitoring soil pH to ensure sustainable farming and preserve soil fertility. Figure 3 shows the maximum soil pH values for each forest type.

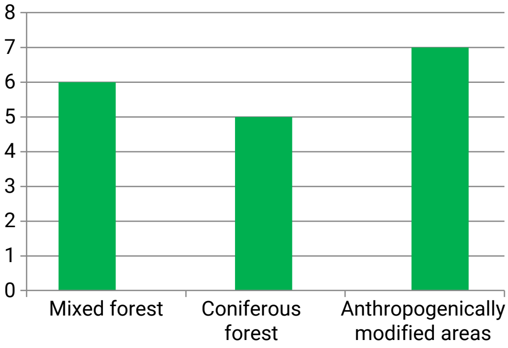

**Figure 3.** Maximum level of soil acidity in different types of forests, soil pH

**Source:** developed by the authors based on Forest Code of Ukraine (1994)

Indicators of nitrate and phosphate concentrations are important components in determining the level of water pollution, since their excessive presence can indicate a negative impact of anthropogenic activities on ecosystems. Measuring nitrate and phosphate concentrations allows not only to assess the current state of water, but also to identify potential sources of pollution, which is crucial for developing effective environmental protection measures (Matkivskyi & Taras, 2024). The study found that the level of water pollution in the mixed forest was assessed as moderate, which indicates that there are no serious environmental threats to the environment and public health. The concentrations of nitrates and phosphates shown in Table 1 remained within acceptable limits, which indicates the effectiveness of water quality control measures. It also highlights the importance of maintaining ecological balance, as the stable state of water resources is crucial for maintaining biodiversity and ecosystem health. Such results may indicate the proper state of water protection zones, which serve as natural barriers that prevent water pollution. Compliance with the standards established for the protection of water resources is an important indicator of the effectiveness of environmental policy in the region, which indicates the need to continue monitoring and implement additional measures to maintain high water quality and ensure sustainable development of the territory (The Law of Ukraine No. 1264-XII, 1991; The Law of Ukraine No. 2456-XII, 1992). The concentrations of nitrates and phosphates in the coniferous forest samples under study were recorded at a level slightly higher than the recommended norms, as can be seen from Table 1, however, these indicators did not reach critical levels that could significantly affect the environmental situation or public health. This indicates the relative stability of the ecological state in the region, but it is important to continue systematic monitoring of these parameters. Regular monitoring will ensure their stability within safe values, and timely detection of any deviations that may lead to potential negative consequences for the environment and human health. Therefore, systematic monitoring is an important tool for maintaining environmental balance and preventing possible threats. Increased levels of environmental pollutants were found in anthropogenic sites, indicating a significant impact of anthropogenic factors such as industrial activity, agriculture, and urbanisation. Nitrate and phosphate concentrations exceed the permissible limits, which is described in detail in Table 1. This is a wake-up call and indicates serious water pollution, which can have negative consequences not only for ecosystems, but also for human and animal health. Increased levels of these pollutants can lead to degradation of water resources, which will affect the quality of water used for drinking and irrigation of crops. In the face of global climate change and growing pressures on natural resources, urgent measures must be taken to monitor and reduce pollution. This should include developing and implementing effective waste management strategies, improving wastewater treatment technologies, and enhancing environmental education among the population. Only thro ugh joint efforts can we ensure environmental safety and preserve natural resources for future generations.

**Table 1.** Concentrations of pollutants in water of different types of forest areas

| Type of forest | Nitrates (mg/l) | Phosphates (mg/l) |
|---|---|---|
| Mixed forest | 5 | 0.5 |
| Coniferous forest | 6.5 | 0.7 |
| Anthropogenically modified areas | 12 | 1.2 |

**Source:** developed by the authors

The data obtained confirmed that the negative impact of anthropogenic factors on the state of forest ecosystems is significant and has numerous negative consequences. In particular, several key aspects were identified that indicate this. Reduction of vegetation biomass in anthropogenically modified areas compared to natural forests. This suggests that human activities such as deforestation, urbanisation, and agricultural development lead to a significant reduction in vegetation, which affects the ecosystem services that forests provide, such as air purification and biodiversity conservation (Resolution of the Cabinet of Ministers of Ukraine No. 521-2014-р, 2014). Reduction of species diversity in anthropogenically modified areas due to changes in natural conditions and human intervention. This means that as a result of anthropogenic impacts, such as the introduction of invasive species, pollution, and habitat changes, many plant and animal species are lost, which can lead to a violation of the ecological balance and reduce the sustainability of ecosystems Increased levels of water pollution and changes in soil acidity in anthropogenically modified areas. In particular, water pollution from industrial waste and agricultural pesticides negatively affects aquatic ecosystems, while changes in soil acidity can lead to degradation of soil resources and reduced forest productivity, which can also have serious consequences for the health of plants and animals that depend on these ecosystems.

Thus, the results highlight the need to take urgent measures to preserve and restore forest ecosystems, and to reduce the negative impact of anthropogenic factors on the environment.

The study also analysed the effectiveness of various environmental indicators to determine the state of forest ecosystems and assess their ability to provide reliable data for management decisions. A key indicator of ecosystem productivity is vegetation biomass. The results showed that mixed forests have the highest biomass of 200 t/ha compared to coniferous forests (160 t/ha) and anthropogenically modified areas (100 t/ha). High levels of biomass in mixed forests confirm their significant ecological productivity, while reduced biomass in anthropogenic areas indicates a negative impact of human activity. Vegetation biomass is an important indicator for assessing ecological productivity and ecosystem health for several reasons. It reflects the total amount of organic mass produced by plants, and thus serves as an indicator of ecosystem productivity, noting its ability to effectively use resources for plant growth and development. Higher biomass is often associated with greater species diversity and the ecosystem’s ability to maintain diverse ecological niches, which contributes to the overall health of the ecosystem. In addition, vegetation performs numerous ecological functions such as water retention, soil structure maintenance, and climate regulation, providing important functions for biodiversity. Therefore, the analysis of vegetation biomass is key to assessing the ability of ecosystems to maintain ecological balance and effectively perform their functions.

Species diversity is critical to ecological stability. The results of the study show that mixed forests have the most plant species (50), while coniferous forests – 35, and anthropogenically modified areas – 20. The high species diversity in mixed forests indicates their ecological stability and ability to support diverse ecological functions. Species diversity is an important indicator of ecological sustainability, as it reflects the ability of an ecosystem to support diverse species and functions that ensure its stability and adaptability. A wide variety of species contributes to an increase in ecological poverty, which helps the ecosystem adapt to changes such as climate change or environmental disturbances. This diversity also supports complex interactions between species, which contributes to the sustainability of the ecosystem and its ability to recover from stressful conditions or disturbances. That is, high species diversity is important for maintaining functional integrity and ecological balance in natural systems. Soil acidity affects the availability of nutrients for plants. The results of the experiment showed that mixed forests have moderately acidic soil (pH 5.5-6), coniferous forests have acidic soil (pH 4.5-5), and anthropogenic altered areas have neutral or alkaline soil (pH 6.5-7). This indicates the specific environmental conditions of each type of forest. Soil acidity is an important environmental indicator, as it directly affects the availability of nutrients for plants. The optimal pH level ensures efficient absorption of elements such as iron and calcium, which is critical for plant growth and development. Deviations from normal pH values can limit the availability of these elements, which leads to a decrease in plant productivity and a violation of the ecological balance. This indicator affects microbiological activity, since some beneficial microorganisms that maintain soil fertility have specific pH requirements. Accordingly, monitoring of soil acidity is key to maintaining the ecological sustainability and productivity of ecosystems, as it helps to identify and correct problems that may arise as a result of its degradation or pollution.

Nitrate and phosphate concentrations are crucial for assessing water pollution. In mixed forests, the level of pollution was moderate, in coniferous forests – slightly increased, and in anthropogenically modified areas – high. This indicates a different level of anthropogenic impact on water resources. Monitoring nitrate and phosphate concentrations is important because these elements are key indicators of water pollution. High concentrations of nitrates and phosphates can indicate a negative impact of anthropogenic factors, such as agriculture or industrial activity, leading to problems such as eutrophication of water bodies. Eutrophication causes excessive algae growth, which can disrupt the ecological balance, reducing oxygen levels in the water and harming aquatic organisms. Therefore, monitoring these concentrations is crucial for assessing water quality, ensuring sustainable water management, and preventing serious environmental problems. Combined analysis of biomass, species diversity, soil acidity, and water pollution levels provides a comprehensive picture of the state of forest ecosystems. These indicators provide important information for making informed management decisions aimed at preserving and restoring ecosystems. Systematic monitoring and analysis of environmental indicators are critical to developing effective management strategies and ensuring the sustainability of natural resources in the long term.

## Discussion

The study carefully analysed a number of environmental indicators, in particular biomass, species diversity and soil acidity in forest ecosystems of the Sumy region. This integrated approach helped to better understand environmental trends and identify changes that occur in these systems under the influence of natural and anthropogenic factors. The findings revealed clear differences between different types of forests, such as coniferous, deciduous, and mixed forests, and between anthropogenically modified areas, which confirms and complements existing scientific data in this area.

The results of the conducted studies indicate that anthropogenically modified areas are characterised by significantly lower biomass and higher soil acidity. These facts confirm the negative impact of human activities on ecosystems, which is a serious problem for the conservation of biodiversity and ecological balance. Studies conducted by R. Bun *et al.* (2024) and J. Reiff *et al.* (2024) are consistent with these findings because it details the increase in greenhouse gas emissions resulting from military operations in Ukraine. This increase in emissions not only worsens the state of the environment, but also contributes to a further increase in the level of acidity in anthropogenically modified areas. The increase in soil acidity is a consequence of increased pollution caused by various factors, in particular, the loss of organic components in the soil, which, in turn, negatively affects land fertility and the ability of ecosystems to recover (Gonfa, 2024).

In the course of the study, it was found that species diversity in forests decreases due to intensive land use, which partially echoes the findings of V. Myroniuk *et al.* (2022) and D. Pilling *et al.* (2020). They analysed in detail the impact of wildfires on various landscapes in Eastern Ukraine, focusing on how such natural disasters can change ecosystems and their biological diversity. The researchers stressed the importance of systematic monitoring and effective management of forests after fires, as this is crucial for restoring ecosystems and maintaining their health. They noted that these strategies should also be applied to anthropogenically modified areas where human activity has significantly affected natural processes. This highlighted the need to integrate environmental principles into land management practices to ensure the sustainable development of forest ecosystems and preserve their biological diversity in the future.

The results of the study confirm the importance of using environmental indicators for a comprehensive assessment of the health of forest ecosystems. This is consistent with the findings presented in the papers by L. Qiao *et al.* (2022), V. Carignan & M. Villard (2002), L. Su *et al.* (2024). Environmental indicators play a key role in understanding changes occurring in ecosystems, as they help to identify trends and patterns that may indicate the state of the environment. In addition, these indicators provide a reliable basis for developing strategies for the conservation and management of natural resources. The use of indicators for monitoring ecosystems has become an important tool that allows not only to assess the sustainability of ecosystems, but also to analyse their performance in various conditions, which contributes to making informed decisions in the field of environmental management and biodiversity conservation (Fedoniuk *et al.*, 2024).

The study found that a high level of species diversity has a positive impact on ecosystem services, which is confirmed by E. Babur *et al.* (2022). This study highlights the critical importance of biodiversity for monitoring the sustainability of forest ecosystems, as species diversity ensures the stability and adaptability of ecosystems to environmental changes. The high level of biodiversity in the forests studied not only contributes to better functioning of ecosystems, but also increases their ability to recover from environmental stresses such as climate change or anthropogenic impacts. This suggests that the conservation and maintenance of biodiversity is key to ensuring the sustainability and productivity of forest ecosystems in the long term (Bragina *et al.*, 2018).

The research results highlighted the urgent need for further research, particularly in the context of climate change and its impact on forest ecosystems, which are important for biodiversity and environmental stability. The study by H. Beygi Heidarlou *et al.* (2023) highlighted the importance of using environmental indicators for a comprehensive assessment of forest health in the long term. These indicators may include species diversity, soil and water conditions, and other factors affecting ecosystems. This highlights the need for continuous monitoring and detailed analysis of changes caused by global climate change; as such changes can have serious consequences for the ecological balance and sustainable development of forest resources.

Research conducted by N. Kovalchuk & N. Tolstushko (2022) identified a significant impact of the war in Ukraine on forest phytocenoses, which is an important aspect of environmental changes in the region. The present study confirms these findings by demonstrating in detail the negative changes in ecosystems resulting from human activity and military conflicts. These changes include, but are not limited to, reduced species diversity, degradation of natural habitats, and disruption of ecological balances. L. Bezlatnia *et al.* (2024) also stressed the critical importance of biodiversity conservation for providing ecosystem services such as air purification, climate regulation, and food security support. Their findings support the results that highlight the importance of biodiversity for ecosystem health and their ability to adapt to environmental changes, highlighting the need for action to protect and restore natural ecosystems, especially in the face of current challenges related to conflict and climate change.

Results of studies conducted by M. Jenssen *et al.* (2021) and P. Eslaminejad *et al.* (2020), concerned the methodology for assessing the integration of forest ecosystems in Germany, which is based on quantitative indicators. These results not only confirm the validity of the research methodology, but also highlight the importance of using clear, evidence-based indicators for a comprehensive assessment of the state of ecosystems, which is critical to ensuring effective management of natural resources and biodiversity conservation. The use of such indicators allows not only to monitor changes in ecosystems, but also to develop strategies for their conservation and restoration, which is an integral part of sustainable development.

M. Ali Mustofa (2022) emphasised the extreme importance of ecotourism as a tool for socio-economic development, and for the conservation of natural ecosystems. Ecotourism not only contributes to economic growth, but can also become an important factor in developing effective forest conservation strategies in Ukraine (Trusova *et al*., 2020). This approach involves the active participation of local communities in the conservation of natural resources, which, in turn, can encourage the development of eco-tourism in regions rich in natural resources. Implementation of such strategies can significantly support the health of forest ecosystems, preserve their biodiversity, and promote the economic development of local communities that depend on the sustainable use of natural resources. Thus, ecotourism becomes not only a means of generating profit, but also an important element in preserving the environment and developing regions.

E.B. Salas (2024) and R. Zuccarini *et al.* (2020) provided detailed data on changes in forest area in Ukraine, which is an important aspect for a deeper understanding of general trends in the country's forest cover. These data can serve as a basis for comparison with these results, which allows identifying specific regional features and changes in ecosystems. The decline in forest cover in Ukraine may be partly due to anthropogenic impacts such as deforestation, environmental pollution, and climate change (Belmega *et al*., 2024). These factors require serious attention from the state and society to ensure sustainable forest management, which will contribute to the conservation of biodiversity and environmental stability in the region.

Summarising, the results of the study not only confirm the conclusions of previous studies, but also complement them, providing new data on the impact of anthropogenic factors, such as changes in land use, air and water pollution, and climate change on the state of forest ecosystems in Ukraine. These new findings are extremely important for understanding the complex relationships between human activity and natural processes occurring in forests. They can serve as a basis for developing effective forest conservation and restoration strategies, which is critical in the context of global changes, such as climate warming, and local environmental challenges faced by various regions of Ukraine. The development of such strategies will not only preserve biodiversity, but also provide environmental, economic, and social benefits for future generations.

## Conclusions

The study found that anthropogenically modified territories in the Sumy Oblast have significantly reduced biomass and increased soil acidity compared to natural forests. It is revealed that species diversity in forest ecosystems is directly related to the level of anthropogenic impact, where intensively exploited territories show less diversity of flora and fauna. The obtained qualitative indicators confirm the negative impact of anthropogenic factors on ecosystems, which is consistent with the results of international studies on biodiversity loss and forest degradation.

Assessment of environmental indicators such as vegetation biomass, species diversity, soil acidity, and nitrate and phosphate concentrations is a key to providing reliable data for making informed management decisions. It was found that mixed forests with high biomass (200 t/ha) and the greatest plant species diversity (50 species) show the highest ecological productivity and stability, which indicates their ability to support various ecological functions. Compared to them, coniferous forests (biomass 160 t/ha, 35 species of flora) and anthropogenically modified areas (biomass 100 t/ha, 20 species of plants) show lower productivity and stability. Soil acidity, which varies from moderately acidic to neutral depending on the type of forest, affects the availability of nutrients for plants, and high concentrations of nitrates and phosphates in anthropogenic areas indicate problems with water pollution. These indicators allow to develop a comprehensive picture of the state of ecosystems, which is necessary for making informed management decisions aimed at preserving and restoring ecosystems, and at effective management of natural resources.

The results highlight the critical importance of preserving natural forest ecosystems and the need to implement effective measures to reduce anthropogenic impact. The data confirm trends in environmental degradation as a result of human activities, which have significant implications for biodiversity and ecosystem services. It is recommended to focus on developing and implementing strategies to reduce anthropogenic impact, such as preserving natural forests, restoring degraded areas, and controlling resource use. It is also necessary to strengthen monitoring of the ecological state of forests and regularly update data on the state of ecosystems.

Further research may focus on the impact of climate change and human activity on environmental performance, and on long-term monitoring of changes in forest ecosystems. It is also useful to investigate the effectiveness of various methods of forest restoration and natural resource management.

The main limitations include the limited scale of the study, which may affect the generality of the results, and the possible unreliability of some measurements due to environmental changes. In addition, the impact of other potential factors, such as climate change or the impact of biological invasions, has not been considered in detail and may affect the accuracy of the data obtained.

## Acknowledgements

None.

## Conflict of Interest

None.

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# Використання екологічних показників для оцінки стану лісових екосистем

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**Анотація**. Метою дослідження був всебічний аналіз ефективності екологічних показників у визначенні стану лісових екосистем, а також їх здатності відображати зміни в екологічному балансі. Під час дослідження було оцінено вплив антропогенних факторів на біомасу, кислотність ґрунту та видове різноманіття лісових екосистем в Сумській області України. Проведено польові дослідження, де визначалися кислотностність ґрунту, біомаса рослин і тварин на антропогенно змінених і природних ділянках лісів з подальшим статистичним аналізом даних. Визначено ступінь деградації лісових територій внаслідок людської діяльності та оцінено екологічні наслідки цих змін для природних систем. Результати показали, що антропогенно змінені ділянки мають знижену біомасу (100 т/га) і видове різноманіття (20 видів рослин), підвищену кислотність ґрунту (pH 6,5-7) та високі концентрації нітратів і фосфатів, в порівнянні з мішаними лісами, де біомаса досягає 200 т/га, видове різноманіття – 50 видів флори, а кислотність ґрунту варіює від помірно кислого до нейтрального (pH 5,5-6). Ці дані підтвердили негативний вплив людської діяльності на екосистеми, зокрема на біомасу та кислотність ґрунту. Встановлено, що екологічні показники дозволяють формувати комплексну картину стану екосистем, що є необхідною для прийняття обґрунтованих управлінських рішень, спрямованих на збереження та відновлення екосистем, а також на ефективне управління природними ресурсами. Отримані результати продемонстрували серйозні екологічні проблеми в наслідок антропогенного впливу на лісові екосистеми. Зменшення біомаси та видового різноманіття, а також підвищення кислотності ґрунту в антропогенно змінених зонах вказують на потребу в терміновому впровадженні заходів для збереження і відновлення природних лісів. Дослідження буде корисним у контексті довгострокового моніторингу екосистем, що дозволить більш детально вивчити динаміку їх зміни

**Ключові слова**: біоіндикатори; біорізномаїття; сталий розвиток; моніторинг довкілля; природне середовище

Received: 28.03.2024; Revised: 16.07.2024; Accepted: 15.08.2024

UKRAINIAN JOURNAL OF FOREST AND WOOD SCIENCE

Journal homepage: https://forestscience.com.ua/en
*Ukrainian Journal of Forest and Wood Science*, 15(3)

UDC 630:614.84:504
DOI: 10.31548/forest/3.2024.43

# Analysis and forecasting of the scale and impact of forest fires on ecosystems of Ukraine

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**Abstract.** Forest fires are one of the most significant environmental problems that have a major impact on biodiversity and climate conditions. The purpose of the study was to investigate the impact of military operations on the ground cover in the area of the Bekhy forestry, which was disturbed by fire. It was revealed that for the period 2022-2023, 15 forest fires were recorded on the territory of the Korosten forest hunting enterprise of the state enterprise "Forests of Ukraine", while the total area covered by fires was 15.13 ha. Overall, the number of fires increased from 5 to 10, but the total area covered by fires decreased from 12.1 to 3.03 ha. At the site of fires in 2022, the pH level increased to lower horizons, with the highest values at microhills (7.55) and microdepressions (7.35). There was a slight increase in the organic carbon content in the upper humus horizon of soils (0.42% on microhills and 0.46% on microdepressions). Bekhy forestry suffered a large forest fire in May 2023, which covered an area of 1.2 ha. The fire hazard assessment of each quarter was carried out separately. In the 50th and 51st compartments, Scots pine was the most fire-prone type of plantings. The 2023 fire site also showed an increase in pH in the lower horizons, with the highest values in microhills (7.35) and microdepressions (7.55). The 2023 fire site showed a decrease in organic carbon content compared to the background sites, with minimal values in the lower parts of the soil profile (0.33% on microdepressions and 0.38% on microhills). The results of the study can be used to develop and implement environmental measures and programmes aimed at restoring forests damaged by fire

**Keywords**: mathematical modelling; probabilistic estimates; Bayes' theorem; carbon; soil profile; background plots

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***Suggested Citation:***
Moroz, V. (2024). Analysis and forecasting of the scale and impact of forest fires on ecosystems of Ukraine. *Ukrainian Journal of Forest and Wood Science*, 15(3), 43-60. doi: 10.31548/forest/3.2024.43.

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## Introduction

One of the main environmental challenges facing Ukraine is the destruction of forests in the north-eastern part of Zhytomyr Oblast due to forest fires. Forest ecosystems in Ukraine are important regulators of climate and biodiversity. The destruction of forests due to fires worsens the quality of soils, water resources, and threatens the existence of many species. The problem of the study is that the impact of the Russian-Ukrainian war contributes to an increase in the area of forests covered by the fire. During the full-scale Russian invasion of Ukraine, more than 3 million ha of forest were affected. According to the State Ecological Inspectorate, approximately 23.3 thousand ha of forests have been burned, some of which have been lost forever (Environmental terrorism of..., 2023).

O.V. Kratko & S.V. Kratko (2023) found that thousands of hectares of forest stands were damaged due to fires after the hostilities. According to the results of this study, it was noted that the most damaged areas were forests in the Luhansk Oblast. I.V. Rybalova *et al*. (2020) noted the largest excess of heavy metals in the soil of coniferous forests of the Chuguivskyi district of the Kharkiv Oblast was noted as a result of a forest fire, in particular copper, zinc, and manganese. According to the conclusions obtained, it was found out that for copper, the excess was 3.41 times, zinc – 2.87 times, and manganese – 2.24 times. E. Korotetska *et al*. (2022) reported the need for statistical analysis and forecasting of the state of forest resources in the Lviv and Kharkiv oblasts. It was established that as a result of a large number of fires, forest stands in the Kharkiv Oblast were in the worst condition compared to the forests of the Lviv Oblast.

A.S. Melnychenko (2023) identified the presence of a problem of chemical contamination in accidents with the release of toxic gases. It is recommended to use chemical neutralisers to maintain a high intensity of gas deposition from the atmosphere. I. Patsev *et al*. (2023) indicated the presence of a problem of mechanical and fire damage to forest lands in the Zhytomyr Oblast. They noted that during the military operations in the period from February 2022 in the Zhytomyr Oblast, 120,000 ha of forest were destroyed. B.V. Molodets (2019) addressed an issue related to the negative effects of wildfires that occurred in the USA from 1992 to 2015. As a result, a product for automated fire risk forecasting was developed. Problem raised in the study by S. Tiwari *et al*. (2022) consisted in the fact that an increase in the solubility of phosphorus in dust and ash occurred with a decrease in PH. It was noted that although acidic soils have a lower pH level, they may have a higher sorption capacity, which leads to a higher amount of phosphorus extracted compared to alkaline soils.

M. García-Carmona *et al*. (2022) outlined the problem of the risk of soil erosion after a forest fire. It was proved that the development of mosses significantly affected the physical and chemical properties of the soil after forest fires. R.E. Loeb & H. Mao (2021) noted that an increase in the pH level can lead to a decrease in reforestation for some tree species. It was found that applying fertilisers to increase the content of phosphorus, potassium, magnesium, and calcium did not lead to a change in natural recovery. D.B. Johnson *et al*. (2024) investigated the problem of increasing pH and decreasing carbon content in organic soil after a fire period. As a result of the research conducted by D.B. Johnson *et al*. (2024), forest fires can lead to complex changes in the composition of the soil microbial community. The content of polycyclic aromatic hydrocarbons at pyrogenic sites remained unexplored.

The purpose of the study was to determine the features of background areas and soils affected by a fire in the ground cover as a result of military operations. Research objectives: development of a mathematical model for predicting forest fires based on the Bayes' statistical mathematical model; investigation of soil degradation after fires.

## Materials and Methods

During the soil contamination study, the methodology used was regulated by the State Standard of Ukraine DSTU 4287:2004 (2004), DSTU ISO 10381-2:2004 (2004). Field studies were conducted on sites located in the Bekhy forestry branch of the state enterprise (SE) "Forests of Ukraine" Korosten forest hunting enterprise (Korosten FHE), which is located in the north-eastern part of Zhytomyr Oblast.

Sections were excavated at each of the sites (30 sites in total). Soil samples were taken from each section along the soil horizons for further analysis. Soil samples were taken for analysis in the first half of August 2023. Samples were dried at room temperature in the shade. The soils were sifted through a sieve with holes of 0.25 mm and 1 mm, depending on chemical analysis. 15 fires were recorded in the branch of Korosten FHE for the period 2022-2023. The total area covered by the fires was 15.13 ha (Fig. 1).

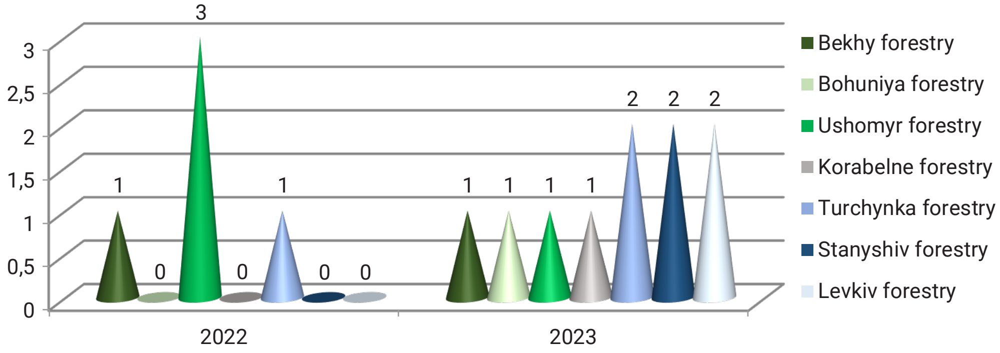

**Figure 1.** Dynamics of the number of cases of forest fires in the Korosten FHE branch of the SE "Forests of Ukraine" for the period 2022-2023

**Source:** compiled by the author

According to the Korosten FHE branch and the State Emergency Service of Ukraine in Zhytomyr Oblast, 5 fires were recorded in three forestries in 2022, covering an area of 12.1 ha. In 2023, 10 fires were registered on the territory of seven forest districts, however, compared to 2022, the area covered by fires has become three times smaller and amounted to 3.03 ha. The study used the Bayesian statistical model to improve the accuracy of predicting the occurrence of forest fires. Potentiometric method for studying the pH of an aqueous suspension on the Expert-01 ionometer (manufactured by Orion company, Ukraine). Titrimetric method for determining organic carbon according to I.V. Tiurin using phenylanthranilic acid. To determine the pH of water extraction by potentiometric method and the organic carbon content, 6 sites were studied: burned areas in 2023, areas affected by the fire in 2022, and background areas. Areas were selected on microrelief (microdepressions and microhills). 87 samples were selected at key sites based on the genetic horizons of soil profiles. The gradation of age groups of plantings by age was divided into the following categories:

- young stands (Y): plantings under 20 years of age;
- middle-aged stands (M): plantings aged from 21 to 40 years;
- ripening stands (R): plantings aged from 41 to 60 years;
- mature stands (Mat): plantings aged from 61 to 80 years;
- overripe stands (Ovr): plantings over 80 years of age.

The following calculations were carried out: organic carbon content by horizons and its subsequent averaging; pH content by horizons and its subsequent averaging; calculation of the probability of each hypothesis; calculation of the probability of the appearance of the attribute $k_1$ in compartment $H_i$. The area of forest lands of the Bekhy forestry district was divided into 120 compartments, so 120 hypotheses H1, H2, ..., H120 can be distinguished. The probability of each hypothesis was calculated using the equation (1):

$$P(H_i) = \frac{S_{H_i}}{S}, \tag{1}$$

where: $\sum_{i=1}^{120} P(H_i)=1$; $P(H_i)$ – a priori probability of hypothesis $H_i$; $S_{H_i}$ – area of the forestry compartment; S – total area of all the forestry compartments under study.

Calculation of the probability of occurrence of the attribute $k_1$ in compartment $H_i$ was determined by equation (2):

$$P(k_{ij}/H_i) = \frac{S_{k_{ij}}}{S_{H_i}}, \tag{2}$$

where: $P(k_{ij}/H_i)$ – probability of occurrence of the attribute $k_i$ in compartment $H_i$; $S_{kij}$ – forest area in the compartment; $S_{H_i}$ – area of the forestry compartment.

The probability of fire occurrence was estimated using the Bayes' equation (3):

$$P(H_i/K) = \frac{P(H_i)\,P(K/H_i)}{\sum_{i=1}^{n} P(H_i)\,P(K/H_i)}, \tag{3}$$

where: $P(H_i)$ – a priori probability of the Hi hypothesis; K – event characterised by a certain set of attributes $k_1, k_2, \dots k_v$; n – total number of possible hypotheses; $P(H_i/K)$ – a posteriori probability of the Hi hypothesis after the results for the complex of attributes of the event K became known; $P(K/H_i)$ – probability of occurrence of the event K with the $H_i$ hypothesis.

## Results

The territory of the Korosten FHE branch was characterised by the Class 1 of fire danger. The estimated logging area for the main use for 2010-2018 was 63830 m³, of which: young coniferous species – 37220 m³, hardwood species – 12900 m³, of which 12900 m³ was in the oak working circle. For analysis, the Bekhy forestry department of the Korosten FHE branch was selected, where a large forest fire occurred in May 2023, covering an area of 1.2 ha (Fig. 2). The area of forests of the Bekhy forestry was 7602 ha.

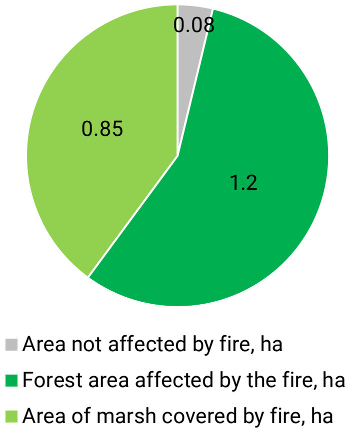

**Figure 2.** Analysis of the area of land plots covered by a fire in the Bekhy forestry in 2023

**Source:** compiled by the author

Using statistics, the fire hazard of each of the compartments throughout the territory of the Bekhy forestry was estimated and fire hazard classes were determined. To determine the probability of a fire in the forest, an area of 4 compartments was taken (50, 51, 60, 61), the total area of which was 270.4 ha with forest stands. According to equation 1, it was determined that:

$$P(H_{50}) = \frac{S_{H_{50}}}{S} = \frac{103}{270.4} = 0.38,$$

$$P(H_{51}) = \frac{S_{H_{51}}}{S} = \frac{80}{270.4} = 0.29,$$

$$P(H_{60}) = \frac{S_{H_{60}}}{S} = \frac{50}{270.4} = 0.18,$$

$$P(H_{61}) = \frac{S_{H_{61}}}{S} = \frac{40}{270.4} = 0.14.$$

To determine the risk of fire probability in each of the compartments, the following characteristics were determined: $k_1$ – composition of forest stands; $k_2$ – crop density; $k_3$ – age of forest stands; $k_4$ – type of forest conditions. Main forest stands of the Bekhy forestry: $k_{11}$ – Scots pine (Sp); $k_{12}$ – white birch (Wb); $k_{13}$ – common oak (Co); $k_{14}$ – black alder (Ba); $k_{15}$ – aspen (A). For each of the compartments, the average value of Scots pine and common oak as a percentage was determined from the formula of rock composition. Table 1 shows the taxation characteristics of compartment 50.

**Table 1.** Taxation indicators for compartment 50

| Stratum | Area, ha | Stand composition | Plantings age group | Relative stand density | Forest type |
|---|---|---|---|---|---|
| 1 | 0.5 | 10Sp+Wb | 5 | 0.7 | B3 OP |
| 2 | 7 | 10Sp+Wb | 6 | 0.6 | A2 P |
| 3 | 8.5 | 7Sp3Wb+Co | 8 | 0.7 | C2 HOP |
| 4 | 2 | 10Sp | 3 | 0.7 | B2 OP |

**Note:** wet oak-pine subor (B3 OP); fresh pine forest (A2 P), fresh hornbeam-oak-pine sugrud (C2 HOP), fresh oak-pine subor (B2 OP)

**Source:** compiled by the author

Pine stands were the most fire-hazardous in compartment 50. Most of the territory of the compartment 50 contained Scots pine stands, the average value of which was 90%. Equation (2) is used to determine its average value for compartment 50:

$$P(k_{11}/H_{50}) = \frac{0.5*1+7*1+8.5*0.7+2*1}{103} = 0.15.$$

Table 2 shows the taxation characteristics of compartment 51.

**Table 2.** Taxation indicators for compartment 51

| Stratum | Area, ha | Stand composition | Plantings age group | Relative stand density | Forest type |
|---|---|---|---|---|---|
| 1 | 0.7 | 10Sp+Ba | 5 | 0.8 | B3 OP |
| 2 | 9 | 8Sp2Wb+Co | 6 | 0.9 | C2 HOP |
| 3 | 9.5 | 8Sp2Wb+Co | 8 | 0.8 | C2 HOP |
| 4 | 3 | 10Sp | 3 | 0.9 | B2 OP |

**Source:** compiled by the author

Pine stands were the most fire-hazardous in compartment 51. The average value of pine stands was 90%. Equation (2) is used to determine its average value for compartment 51:

$$P(k_{11}/H_{51}) = \frac{0.7*1+9*0.5+9.5*0.8+3*1}{80} = 0.19.$$

Table 3 shows the taxation characteristics of compartment 60.

**Table 3.** Taxation indicators for compartment 60

| Stratum | Area, ha | Stand composition | Plantings age group | Relative stand density | Forest type |
|---|---|---|---|---|---|
| 1 | 0.4 | 10Co+Ba | 4 | 0.9 | B3 OP |
| 2 | 6 | 6Co4Wb+A | 7 | 0.8 | C2 HOP |
| 3 | 5 | 6Co+4Wb+A | 9 | 0.7 | C2 HOP |
| 4 | 8 | 10Co | 4 | 0.6 | B2 OP |

**Source:** compiled by the author

Common oak stands were the most fire-hazardous in compartment 60. The average value of commonoakstandswas80%.Equation(2)isusedto determine its average value for compartment 60:

$$P(k_{13}/H_{60}) = \frac{0.4*1+6*1+5*1+8*1}{50} = 0.38.$$

Table 4 shows the taxation characteristics of compartment 61.

**Table 4.** Taxation indicators for compartment 61

| Stratum | Area, ha | Stand composition | Plantings age group | Relative stand density | Forest type |
|---|---|---|---|---|---|
| 1 | 0.3 | 10Co+A | 6 | 0.8 | B3 OP |
| 2 | 5 | 6Co4Wb+Ba | 8 | 0.9 | C2 HOP |
| 3 | 8 | 6Co4Wb+A | 10 | 0.6 | C2 HOP |
| 4 | 9 | 10Co | 7 | 0.4 | B2 OP |

**Source:** compiled by the author

Common oak stands were the most fire-hazardous for compartment 61. The average value of oak stands was 82%. Equation (2) is used to determine its average value for compartment 61:

$$P(k_{13}/H_{61}) = \frac{0.3*1+5*1+8*1+9*1}{40} = 0.55.$$

The most fire-prone areas were those with a stand density of 0.7, 0.8, and 0.9. According to the stand density, the following groups can be distinguished: $k_{21}$ – density 0.7-1; $k_{22}$ – density 0-0.6. There are medium-sized (1, 2, 3, and 4 strata) plantations in compartment 50. According to equation (2), the average value of stand density for compartment 50 was calculated:

$$P(k_{21}/H_{50}) = \frac{0.5+8.5+2}{103} = 0.1.$$

On the territory of compartment 51 there are high-quality (1, 2, 3, and 4 strata) plantings. Using equation (2), the average stand density value for compartment 51 was calculated:

$$P(k_{21}/H_{51}) = \frac{0.7+9+9.5+3}{80} = 0.27.$$

On the territory of compartment 60, there are high-density (1st and 2nd strata) and medium-density (3rd and 4th strata) stands. Using equation (2), the average stand density value for compartment 60 was calculated:

$$P(k_{21}/H_{60}) = \frac{0.4+6+5}{50} = 0.22.$$

On the territory of compartment 61 there are high-density (1st and 2nd strata) and medium-density (3rd stratum) and low-density (4th stratum) stands. Using equation (2), the average stand density value for compartment 61 was calculated:

$$P(k_{21}/H_{61}) = \frac{0.3+5}{40} = 0.13.$$

The following age groups are distinguished: $k_{31}$ – age groups 2 and 3 (young stands of Class 1 and 2 up to 40 years); $k_{32}$ – age groups 4 and 8 (others over 40 years old). In compartment 50, on average, by age group, plantings belong to ripening stands (71-80 years), which was 90%. Fire hazard class 1 – presence of plantings of age groups 2 and 3 (4th stratum):

$$P(k_{31}/H_{50}) = \frac{S_{k_{31}}}{S_{H_{50}}} = \frac{2}{103} = 0.01.$$

Fire hazard classes 2-4 – age groups 4-8 (1st, 2nd, and 3rd strata):

$$P(k_{32}/H_{50}) = \frac{S_{k_{32}}}{S_{H_{50}}} = \frac{16}{103} = 0.15.$$

In compartment 51, on average, by age group, plantings belong to ripening stands (71-80 years), which was 90%. Fire hazard Class 1 – presence of plantings of age groups 2 and 3 (4th stratum):

$$P(k_{31}/H_{51}) = \frac{S_{k_{31}}}{S_{H_{51}}} = \frac{3}{80} = 0.03.$$

Fire hazard classes 2-4 – presence of plantings of age groups 4-8 (1st, 2nd, and 3rd strata):

$$P\ (k_{32}/H_{51}) = \frac{S_{k_{32}}}{S_{H_{51}}} = \frac{19.2}{80} = 0.24.$$

In compartment 60, on average, by age group, plantings belong to ripening stands (71-80 years), which was 90%. Fire hazard classes 2-4 – presence of plantings of age groups 4-8 (1st, 2nd, and 4th strata) and 9 (3th stratum):

$$P(k_{32}/H_{60}) = \frac{S_{k_{32}}}{S_{H_{60}}} = \frac{19.4}{50} = 0.38.$$

In compartment 61, on average, by age group, plantings belong to ripening stands (71-80 years), which was 90%. Fire hazard classes 2-4 – presence of plantings of age groups 4-8 (1st, 2nd, and 4th strata) and 9 (3rd statum):

$$P(k_{32}/H_{61}) = \frac{S_{k_{32}}}{S_{H_{60}}} = \frac{22.3}{40} = 0.55.$$

For compartment 50:
Fire hazard class 1 (4th stratum):

$$P(k_{41}/H_{50}) = P(k_{31}/H_{50}) = \frac{S_{k_{31}}}{S_{H_{50}}} = \frac{2}{103} = 0.01.$$

Fire hazard class 2 (2nd and 3rd strata):

$$P(k_{42}/H_{50}) = \frac{S_{k_{42}}}{S_{H_{50}}} = \frac{7+8.5}{103} = 0.15.$$

Fire hazard class 3 (1st stratum):

$$P(k_{43}/H_{50}) = \frac{S_{k_{42}}}{S_{H_{50}}} = \frac{0.5}{103} = 0.004.$$

For compartment 51:
Fire hazard class 1 (4th stratum):

$$P(k_{41}/H_{51}) = P(k_{31}/H_{51}) = \frac{S_{k_{31}}}{S_{H_{51}}} = \frac{3}{80} = 0.03.$$

Fire hazard class 2 (2nd and 3rd strata):

$$P(k_{42}/H_{51}) = \frac{S_{k_{42}}}{S_{H_{51}}} = \frac{9+9.5}{80} = 0.23.$$

Fire hazard class 3 (1st stratum):

$$P(k_{43}/H_{51}) = \frac{S_{k_{42}}}{S_{H_{51}}} = \frac{0.7}{80} = 0.008.$$

For compartment 60:
Fire hazard class 1 (4th stratum):

$$P(k_{41}/H_{60}) = P(k_{31}/H_{60}) = \frac{S_{k_{31}}}{S_{H_{60}}} = \frac{8}{50} = 0.16.$$

Fire hazard class 2 (2nd and 3rd strata):

$$P(k_{42}/H_{60}) = \frac{S_{k_{42}}}{S_{H_{60}}} = \frac{6+5}{50} = 0.22.$$

Fire hazard class 3 (1st stratum):

$$P(k_{43}/H_{60}) = \frac{S_{k_{42}}}{S_{H_{60}}} = \frac{0.4}{50} = 0.008.$$

For compartment 61:
Fire hazard class 1 (4th stratum):

$$P(k_{41}/H_{61}) = P(k_{31}/H_{61}) = \frac{S_{k_{31}}}{S_{H_{61}}} = \frac{9}{40} = 0.22.$$

Fire hazard class 2 (2nd and 3rd strata):

$$P(k_{42}/H_{61}) = \frac{S_{k_{42}}}{S_{H_{61}}} = \frac{5+8}{40} = 0.32.$$

Fire hazard class 3 (1st stratum):

$$P(k_{43}/H_{61}) = \frac{S_{k_{42}}}{S_{H_{61}}} = \frac{0.3}{40} = 0.007.$$

The probability of fire occurrence in compartment 50 was calculated:

Fire hazard class 1:

$$P(H_{50})P(K_1/H_{50}) = P(H_{50})P(k_{11}/H_{50})$$
$$P(k_{21}/H_{50})P(k_{31}/H_{50})P(k_{41}/H_{50}) =$$
$$= 0.38 \ast 0.15 \ast 0.1 \ast 0.01 \ast 0.01 = 0.0000005.$$

Fire hazard class 2:

$$P(H_{50})P(K_2/H_{50}) = P(H_{50})P(k_{11}/H_{50})$$
$$P(k_{21}/H_{50})P(k_{32}/H_{50})P(k_{42}/H_{50}) =$$
$$= 0.38 \ast 0.15 \ast 0.1 \ast 0.15 \ast 0.15 = 0.0001.$$

Fire hazard class 3:

$$P(H_{50})P(K_3/H_{50}) = P(H_{50})P(k_{11}/H_{50})$$
$$P(k_{21}/H_{50})P(k_{32}/H_{50})P(k_{43}/H_{50}) =$$
$$= 0.38 \ast 0.15 \ast 0.1 \ast 0.15 \ast 0.004 = 0.000003.$$

According to the calculation results, fire hazard class 2 is most probable for compartment 50. The probability of fire occurrence in compartment 51 was calculated:

Fire hazard class 1:

$$P(H_{51})P(K_1/H_{51}) = P(H_{51})P(k_{11}/H_{51})$$
$$P(k_{21}/H_{51})P(k_{31}/H_{51})P(k_{41}/H_{51}) =$$
$$= 0.29 \ast 0.19 \ast 0.27 \ast 0.03 \ast 0.03 = 0.00001.$$

Fire hazard class 2:

$$P(H_{51})P(K_2/H_{51}) = P(H_{51})P(k_{11}/H_{51})$$
$$P(k_{21}/H_{51})P(k_{32}/H_{51})P(k_{42}/H_{51}) =$$
$$= 0.29 \ast 0.19 \ast 0.27 \ast 0.24 \ast 0.23 = 0.0008.$$

Fire hazard class 3:

$$P(H_{51})P(K_3/H_{51}) = P(H_{51})P(k_{11}/H_{51})$$
$$P(k_{21}/H_{51})P(k_{32}/H_{51})P(k_{43}/H_{51}) =$$
$$= 0.29 \ast 0.19 \ast 0.27 \ast 0.24 \ast 0.008 = 0.00002.$$

According to the calculation results, fire hazard class 2 is most likely for compartment 51. The probability of fire occurrence in compartment 60 was calculated:

Fire hazard class 1:

$$P(H_{60})P(K_1/H_{60}) = P(H_{60})P(k_{13}/H_{60})$$
$$P(k_{21}/H_{60})P(k_{32}/H_{60})P(k_{41}/H_{60}) =$$
$$= 0.18 \ast 0.38 \ast 0.22 \ast 0.38 \ast 0.16 = 0.0009.$$

Fire hazard class 2:

$$P(H_{60})P(K_2/H_{60}) = P(H_{60})P(k_{13}/H_{60})$$
$$P(k_{21}/H_{60})P(k_{32}/H_{60})P(k^{42}/H_{60}) =$$
$$= 0.18 \ast 0.38 \ast 0.22 \ast 0.38 \ast 0.22 = 0.001.$$

Fire hazard class 3:

$$P(H_{60})P(K_3/H_{60}) = P(H_{60})P(k_{13}/H_{60})$$
$$P(k_{21}/H_{60})P(k_{32}/H_{60})P(k_{43}/H_{60}) =$$
$$= 0.18 \ast 0.38 \ast 0.22 \ast 0.38 \ast 0.008 = 0.00004.$$

According to the calculation results, fire hazard class 2 is most probable for compartment 60. The probability of fire occurrence in compartment 61 was calculated:

Fire hazard class 1:

$$P(H_{61})P(K_1/H_{61}) = P(H_{61})P(k_{13}/H_{61})$$
$$P(k_{21}/H_{61})P(k_{32}/H_{61})P(k_{41}/H_{61}) =$$
$$= 0.14 \ast 0.55 \ast 0.13 \ast 0.55 \ast 0.22 = 0.001.$$

Fire hazard class 2:

$$P(H_{61})P(K_2/H_{61}) = P(H^{61})P(k_{13}/H_{61})$$
$$P(k_{21}/H_{61})P(k_{32}/H_{61})P(k_{42}/H_{61}) =$$
$$= 0.14 \ast 0.55 \ast 0.13 \ast 0.55 \ast 0.32 = 0.001.$$

Fire hazard class 3:

$$P(H_{61})P(K_3/H_{61}) = P(H_{61})P(k_{13}/H_{61})$$
$$P(k_{21}/H_{61})P(k_{32}/H_{61})P(k_{43}/H_{61}) =$$
$$= 0.14 * 0.55 * 0.13 * 0.55 * 0.007 = 0.00003.$$

For compartment 61, fire hazard classes 1 and 2 are most likely. To determine the full probability of Class 2 fire in the forest, the $K_2$ event was selected:

$$P(K_2) = P(H_{50})P(K_2/H_{50}) + P(H_{51})$$
$$P(K_2/H_{51}) + P(H_{60})P(K_2/H_{60}) + P(H_{61})P(K_2/H_{61}) =$$
$$= 0.0001 + 0.0008 + 0.001 + 0.001 = 0.0029.$$

Using equation 3, the fire hazard of each compartment was estimated:

$$P(H_{50}/K_2) = \frac{P(H_{50})\,P(K_2/H_{50})}{P(K_2)} = \frac{0.0001}{0.0029} = 0.034.$$

$$P(H_{51}/K_2) = \frac{P(H_{51})\,P(K_2/H_{51})}{P(K_2)} = \frac{0.0008}{0.0029} = 0.27.$$

$$P(H_{60}/K_2) = \frac{P(H_{60})\,P(K_2/H_{60})}{P(K_2)} = \frac{0.001}{0.0029} = 0.34.$$

$$P(H_{61}/K_2) = \frac{P(H_{61})\,P(K_2/H_{61})}{P(K_2)} = \frac{0.001}{0.0029} = 0.34.$$

According to calculations, among compartments 50, 51, 60, 61, the most probable occurrence of a Class 2 fire is in compartments 60, 61, 51, and 50. The soils of the Bekhy forestry of the Korosten FHE are characterised by a neutral or slightly alkaline reaction. The results of the study of acid-base conditions in the studied soils exposed to fire are presented in Table 5.

**Table 5.** Indicators of average pH values in soils depending on the location in the terrain by burning areas and background area

| Indicator | | | pH |
|---|---|---|---|
| Plot No. 1 affected by fire in 2022 | Microhill | Lower horizon | 7.55 |
| | | Upper horizon | 7.38 |
| | Microdepression | Lower horizon | 7.35 |
| | | Upper horizon | 7.35 |
| Plot No. 2 affected by fire in 2023 | Microhill | Lower horizon | 7.35 |
| | | Upper horizon | 7.3 |
| | Microdepression | Lower horizon | 7.55 |
| | | Upper horizon | 7.35 |
| Background areas | Microhill | Lower horizon | 8.4 |
| | | Upper horizon | 7.8 |
| | Microdepression | Lower horizon | 8.1 |
| | | Upper horizon | 7.9 |

**Source:** compiled by the author

The measured pH values in the burning and background areas, mainly in the microrelief, showed the following results. In all soils, the pH values vary from the upper horizons to the lower ones from neutral to slightly alkaline. In the background plots, an increase in PH was observed at microhills and microdepressions of increase to the lower horizons. The lowest pH value is achieved in the upper horizons of soils of microhills and microdepressions (7.8 and 7.9, respectively). The highest pH value of background sites was observed in the lower soil horizons of 8.1 on microdepressions and 8.4 on microhills. At the site of fires in 2022, there was also an increase in the reaction of the environment to the lower soil horizons and a higher pH value at microhills. The highest indicator was observed in the lower horizons: on microhills – 7.55, on microdepressions – 7.35. The minimum values were reached in the upper horizons of microhills and microdepressions (7.38 and 7.35, respectively). In the areas of fires in 2023, the pH value differed in microrelief. Mostly on microdepressions, the pH is slightly higher in the upper part of the profile (7.35) than on microhills (7.3). The maximum pH value was reached in the lower soil horizon (Cca or Cs) and was 7.35 on microhills and 7.55 on microdepressions. Probably, the tendency to decrease the pH values in post-fire soils is explained by the fact that ash water-soluble compounds, penetrating into the soil, saturate the absorption complex with alkaline earth elements, compared to background areas.

The most important negative environmental effect of fires is the loss of organic matter by the ecosystem as a whole, including the loss of soil organic matter (Matkivskyi & Taras, 2024). With the help of studies, it was found that in soils exposed to thermal effects, a tendency to reduce the humus content in the 0-10 cm layer was observed. Fires have the greatest impact directly on the upper humus horizon of soils. The organic carbon content of the forests is decreasing from baseline to fire. In background areas, organic carbon values are higher than in areas of fires of different ages. The maximum organic carbon content in background soils ranged from 0.4% in microhills to 0.7% in microdepressions. The maximum value of organic carbon in background soils ranged from 0.4% in microhills and 0.7% in microdepressions. The 2022 fire site showed a slight increase in organic carbon in the upper humus horizon of soils, approximately 0.42% in microhills and 0.46% in microdepressions, compared to a less ancient fire. In the lower parts of the soil profile, the minimum organic carbon values of approximately 0.35% were achieved. In the 2023 fires, the organic carbon content was only 0.33% and 0.38% (microdepression and microhill, respectively), decreasing down the profile – 0.1% and 0.12% (microdepression and microhill, respectively).

Therefore, the decrease in organic carbon content is directly related to the activity of fires. Most likely, this is due to the thermal effect of fires on the top layer of soils, which led to the transformation and destruction of the humus horizon of soils.

## Discussion

Analysing the results of the study, it can be concluded that the increase in the intensity of forest fires as a result of military operations negatively affected natural ecosystems. In particular, one of the most important problems is the destruction of the humus horizon of soils. The humus horizon is the top layer of soil rich in organic substances that ensure soil fertility and help to preserve moisture. As a result of the ecocide carried out by the aggressor state, in particular, the upper fertile layer of chernozem soils was destroyed. Over the past 100 years, Ukrainian soils have lost 30% of humus. Due to the impact of the war, the process of destruction accelerated. Fires burn organic material in the soil, such as plant remains, leaves, and roots (Shahini *et al*., 2024). There is a decrease in the content of organic carbon, which is an important component of soil fertility.

It was found that the increase in the intensity of forest fires has had serious negative consequences for the ecosystem, in particular for forest soils, due to a decrease in the content of organic carbon in the soil (Skliar *et al*., 2020). Similar question was considered by F. Niccoli *et al*. (2023). They found that the fires had significantly reduced the trees' ability to photosynthesise and absorb carbon dioxide ($CO_2$) due to defoliation and crown damage. Tree growth has decreased and water use has changed, which has affected the ability to store carbon and mitigate climate change. The results of the current study did not coincide with the conclusions of F. Niccoli *et al*. (2023), since they analysed the effect of organic carbon on soils on microhills and microdepressions of the lower and upper soil horizons.

It was noted that the organic carbon content of the background plots before the fires decreased, which is associated with the thermal impact of fires on the topsoil. The same problem was considered by Z. Cheng *et al*. (2023). They found that all three degrees of fire significantly increased microbial carbon concentrations in the soil, moisture content, and total nitrogen content, but they significantly reduced the available potassium content in the soil compared to unburned taiga forests. Indeed, fires do have a complex effect on soil properties, which was due to an increase in microbial carbon, since microorganisms can decompose carbon residues, in addition, potassium is an easily mobile element and can move quickly from the surface layer of the soil, especially during rains after a fire (Yanitskyi, 2024).

It has been found that the use of data from the Bayes' statistical mathematical model for fire assessment has resulted in a fairly accurate prediction of forest fires. A similar issue was studied by G. Alarcon-Aguirre *et al*. (2022). The researchers found that Sentinel-1's cross-polarisation optical image data has sufficient accuracy to detect and quantify fires. This statement should be accepted because Sentinel-1's cross-polarising optical images can indeed be a useful tool for detecting and assessing fires, especially when combined with satellite imagery data from the space remote sensing mission (Sentinel-2) and the Earth's remote area observation programme (Landsat).

According to the results of the study, it was shown that oak forests, in particular common oak stands, were the most fire-hazardous for compartments 60 and 61 of the Bekhy forestry of the Korosten FHE branch. A similar issue was studied by M. Heenatigala & G. Duh (2022). Based on the work of these researchers, it was established that certain types of forests, such as dry monsoon forests, were particularly vulnerable to forest fires and required priority restoration. Thus, both studies present different aspects of the study of forests and their fire hazard: determination of the most fire-prone composition of forest stands in this study and analysis of vulnerability to fires by M. Heenatigala & G. Duh.

Soils that were exposed to fire in 2022 and 2023 showed higher pH values than in the background areas of the upper soil horizons on microhills and microdepressions. The dynamics of these indicators were considered by E. Nandakumar *et al*. (2024), where specified, that as a result of a forest fire, a higher pH level of the soil was found on the burnt surface of the soil than on the unburned land area. Similar conclusions were obtained in the study, according to which it was revealed that in the background areas the lowest pH value was reached in the upper horizons of soils of microhills of 7.8 and microdepressions of 7.9, but the highest pH value was observed in the lower horizons of soils on microdepressions – 8.1 and on microhills – 8.4. In the areas of fires in 2022, the lowest pH values were established in the upper horizons of microhills at 7.38 and microdepressions – 7.35, and in 2023, the minimum pH values were reached in the upper horizon of soils, which was 7.35 on microdepressions, 7.3 on microhills.

According to statistics on taxation indicators of compartments, it was revealed that the most vulnerable plant to fires for compartments 50 and 51 was Scots pine, but for compartments 60 and 61 such a plant was common oak. A similar issue was considered by K. Raj *et al*. (2023). Based on the results obtained by them, it was noted that the use of the statistical method of the Canadian fire weather index and the Australian fire hazard index to assess vegetation vulnerability to fire has contributed to the creation of effective and accurate models of forest fires based on the use of stochastic and mathematical methods. The conclusions by K. Raj *et al*. indicate that stochastic and mathematical methods allow developing predictive models that consider random factors and natural changes, such as changes in weather and climate.

It was demonstrated that the mathematical model for predicting the risk of forest fires had high accuracy, since modern mathematical models can work with large amounts of data, which increases the accuracy of forecasts. A similar study was conducted by Y. Li *et al*. (2020). According to the researchers, the Random Forest model showed the highest accuracy – 89.2%, compared to such models as an artificial neural network, a network of radial basis functions, and a support vector machine, which indicated its effectiveness in predicting the likely occurrence of forest fires. The authors agree with this statement, since the Random Forest model is an effective machine learning method for various classification and regression tasks due to its ability to process a large number of input variables, reduce the risk of overtraining, and provide high accuracy of forecasts.

It was recorded that the most likely occurrence of a Class 2 fire was in compartments 60 and 61, the fire hazard coefficient of which was 0.34. Research on a similar issue was carried out by R. Bagherabadi *et al*. (2022). The map of high-risk areas for forest fires showed that the largest part of the territory covered by forest fires included areas with medium risk, which amounted to 33.43%. The results obtained in the presented study differ from the conclusions drawn in the paper by R. Bagherabadi *et al*. (2022), which may be due to differences in the research methods they used, such as the geographic information systems method in the analysed study and the Bayes' statistical mathematical model method in the present study.

The mathematical model for predicting the risk of forest fires is highly effective, since it considered the probability of fire based on various factors, such as the composition of plantings, stand density, the age of forest stands, and the type of forest conditions. The issue under discussion was investigated by D.D. Perrakis *et al*. (2023). Based on the results of their study, it was noted, that the updated models based on a systematic approach to fire initiation and propagation were more efficient than fixed-fuel models. The authors of this study agree with this statement, since the improved fire probability models considered variables of the fire environment, such as wind speed, destruction of fuel layers, humidity of the litter, and consumption of the amount of fuel used by the fire on the surface.

In Zhytomyr Oblast, in 2023, 10 fires were registered on the territory of seven forest districts, but compared to 2022, the area covered by fires has become three times smaller, which is conditioned by active measures to restore forest ecosystems, including planting trees less susceptible to fires. The study of a similar issue was carried out by S. Connor *et al*. (2021). Their research found that prolonged drought caused the death of pine plantations, but also a decrease in the number of fires, which led to the restoration of the coastal pine forest. This statement can be agreed with, as coastal pine forests do have a high capacity for natural regeneration, provided there are no significant negative factors such as fires.

Using statistical data, it is possible to identify the fire hazard of each quarter separately throughout the entire territory of Bekhy forestry. Such an issue was studied by M. Ibraheem *et al*. (2024). It was revealed that the Forest Defender Fusion early detection system has achieved high efficiency in identifying and monitoring forest fires with an accuracy of 99.86%, significantly exceeding the performance of other existing models that use input red, green, blue, and infrared image analysis. We should agree with the results of this study, since the Forest Defender Fusion early detection system really demonstrated efficiency in using advanced technologies for monitoring and detecting fires, which allowed for timely response and minimising environmental damage.

Inventory reduction detected organic carbon at the sites of fires in 2023. A similar issue was studied by H. Bargali *et al*. (2024). Based on the results of their work, it can be stated that the frequent occurrence of fires has led to a significant reduction in organic carbon stocks, especially in high-frequency fire classes. When plant biomass is burned, carbon is released into the atmosphere as carbon dioxide ($CO_2$), which leads to a decrease in total organic carbon reserves in ecosystems (Babak *et al.*, 2021).

Content of organic carbon decreased down the profile by 0.1% on microdepressions and 0.12% on microhills. A similar problem has been investigated by B.M. Rodríguez-Cardona *et al*. (2020). It was shown that forest fires increased nitrate concentrations over a ten-year period, which led to a decrease in dissolved organic carbon and nitrogen concentrations over a fifty-year period. Agreeing with the statement, it should be noted that the opinion of B.M. Rodríguez-Cardona *et al*. is correct, as the burning of plant mass releases nitrates that can be leached into the soil, increasing the concentration of nitrates in the long term.

An increase in organic carbon concentration of approximately 0.42% was detected at the 2022 burn site, with a 0.46% increase in microhills, compared to 0.42% in microdepressions. A similar issue has been investigated by I. Megremi *et al*. (2024). They presented the results, according to which an increase in the concentration of organic carbon in the areas affected by the fire indicated incomplete combustion of vegetation. Similar conclusions were obtained in this study, since the presented results also indicate the presence of increased carbon content in the upper humus horizon of soils.

The presented study reported that the pH of the soil from 7.9 to 7.55 was in a slightly alkaline range, which contributed to a good growth of many types of tree stands. A similar issue was studied by S.J. Rance *et al*. (2020). The researchers found that phosphorus increased the pH of the soil and stimulated tree growth, while nitrogen and sulphur lowered the pH. This formulation of the researchers' conclusions should be agreed with, since phosphorus can actually affect the pH of the soil, increasing the PH concentration, since phosphate fertilisers have alkaline properties. At the same time, nitrogen and sulphur can lower the pH of the soil due to the generation of acidic compounds during their decomposition (Shahini *et al.*, 2022).

After the fire, the highest pH values were observed in the lower horizons, while organic carbon was lost most in the upper horizon after the fire. This issue was also studied by T. Whitman *et al*. (2022). According to the researchers, five years after the fire, the plant community, pH, and total carbon did not acquire the same state as before the fire, while bacterial communities recovered throughout the area covered by the fire. According to T. Whitman *et al*. (2022), since bacteria have a high potential to adapt and multiply rapidly in new conditions, even with changes in pH, humidity, and organic matter levels.

The decrease in organic carbon content is directly related to the thermal effect of fires on the topsoil. This topic was investigated by J. Adkins & J.R. Miesel (2021). It is shown that at high soil temperatures (up to 200°C), the soil's ability to absorb carbon decreased. Similar conclusions were obtained in the presented study, since the results showed a tendency to reduce the carbon content, which led to the destruction of the humus horizon of soils.

A decrease in organic carbon content was detected at the 2023 burn sites. A similar topic was studied by A. Girona-García *et al*. (2024). It was noted that organic carbon erosion can absorb up to 13% of carbon emissions within one year of a fire. The findings of the present study coincided with the conclusions of A. Girona-García *et al*. (2024), since they monitored the organic carbon content in soils before and after fires, and also found a decrease in the organic carbon content after fires.

In the background areas, there was a higher level of organic carbon compared to the areas by fires. A similar topic was studied by S.C. Panico *et al*. (2022). It was shown that in the post-fire period, there was a significant increase in the level of organic substances and the ratio of carbon to nitrogen (C/N). According to S.C. Panico *et al*. (2022), an increase in organic matter and the C/N ratio may indicate the destruction of organic matter and its carbon-nitrogen composition as a result of a fire.

In 2022, all organic carbon reserves in the soil increased linearly over time after the fire. The same topic was considered by B. Andrieux *et al*. (2020). Based on the findings, it was shown that soil organic carbon stocks increased at 0.02 and 0.12 MgC/ha$^{-1}$ year$^{-1}$ after the fire. It is worth agreeing with B. Andrieux *et al*. (2022), since fire can alter the structure and composition of the soil, which can contribute to faster decomposition of organic materials and, consequently, the accumulation of organic carbon.

In this section, a literature review was conducted and studies on the impact of forest fires on the ecosystem, in particular on changes in soil and photosynthesis of trees, were considered. A study was conducted on the impact of forest fires on soil properties and the vulnerability of different types of forests to forest fires, including dry monsoon forests.

## Conclusions

The results of the study of the impact of fires on soil properties showed that as a result of fires, there was a tendency to decrease the pH values in soils of the post-fire period, which was explained by the fact that ash water-soluble compounds, when penetrating into the soil, can saturate the absorbing complex with alkaline earth elements. In the background plots, the pH level increased to the lower horizons, with the maximum value in the lower part of the profile (8.1 for microdepressions and 8.4 for microhills). In the soils covered by the fire, a decrease in carbon was observed, which is associated with the destruction of the upper horizon due to thermal exposure. The maximum organic carbon content was found in background areas (0.4% in microhills and 0.7% in microdepressions).

In the Zhytomyr Oblast, in 2022, 5 fires were recorded on the territory of three forest districts, covering an area of 12.1 ha, and in 2023 – 10 fires on the territory of seven forest districts, covering an area of 3.03 ha. Using the model used, the probabilities of fires occurring in each quarter were determined, and factors influencing their occurrence were considered, such as the composition of forest stands, stand density, the age of forest stands, and the type of forest conditions. For compartments 50, 51, 60, and 61, the total area of which was 270.4 ha, the probability of fire was determined. The highest probability was for compartment 50 (0.38), and the lowest for compartment 61 (0.14). As a result of the study, common oak stands were the most fire-prone for compartments 60 and 61. Pine stands were the most dangerous for compartments 50 and 51.

In the review of studies of the territories covered by forest fires in the Zhytomyr Oblast, it is necessary to note the unavailability of some data on the state of soils for analysis. The study did not consider the impact of fires on soil biological components, such as microorganisms and plant root systems, which can also affect ecosystem recovery. Areas of further research may include the introduction of regular monitoring of changes in the physical and chemical properties of soils in areas covered by fires, to assess the long-term consequences of fires, improving models for predicting the probability of fires, considering new data on the state of soils and afforestation, and climate change.

## Acknowledgements

None.

## Conflict of Interest

None.

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# Аналіз та прогнозування масштабів та наслідків впливу лісових пожеж на екосистеми України

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**Анотація**. Лісові пожежі є однією з найбільш значущих екологічних проблем, які мають суттєвий вплив на біорізноманіття та кліматичні умови. Метою дослідження було вивчення впливу військових дій на ґрунтовий покрив у зоні Бехівського лісництва, який порушений пожежею. По результатам дослідження виявлено, що за період 2022-2023 років на території філії “Коростенське лісомисливське господарство” державного підприємства “Ліси України” зафіксовано 15 лісових пожеж, при цьому загальна охоплена пожежами площа склала 15,13 гектарів. Загалом, кількість пожеж збільшилася від 5 до 10, але загальна площа, охоплена пожежами, зменшилася з 12,1 до 3,03 гектарів. На ділянці пожеж у 2022 році спостерігалося підвищення рівня pH до нижніх горизонтів, з найбільшим значенням на мікропідвищеннях (7,55) та на мікропониженнях (7,35). Відмічено невелике збільшення вмісту органічного вуглецю у верхній гумусовому горизонті ґрунтів (0,42 % на мікропідвищеннях і 0,46 % на мікропониженнях). Бехівське лісництво зазнало великої лісової пожежі в травні 2023 року, яка охопила площу 1,2 гектарів. Була проведена оцінка пожежонебезпечності кожного кварталу окремо. У 50 та 51 кварталі сосна звичайна виявилася найбільш пожежонебезпечним видом насаджень. Ділянка пожеж у 2023 році також показала підвищення pH у нижніх горизонтах, з найвищими значеннями на мікропідвищеннях (7,35) та на мікропониженнях (7,55). Ділянка пожеж у 2023 році демонструвала зменшення вмісту органічного вуглецю в порівнянні з фоновими ділянками, з мінімальними значеннями в нижніх частинах ґрунтового профілю (0,33 % на мікропониженнях і 0,38 % на мікропідвищеннях). Результати дослідження можуть бути використані з метою розробки та впровадження екологічних заходів та програм, спрямованих на відновлення пошкоджених пожежею лісів

**Ключові слова**: математичне моделювання; імовірнісні оцінки; теорема Байєса; вуглець; ґрунтовий профіль; фонові ділянки

Received: 02.05.2024; Revised: 01.08.2024; Accepted: 15.08.2024

UKRAINIAN JOURNAL OF FOREST AND WOOD SCIENCE

UKRAINIAN JOURNAL OF FOREST AND WOOD SCIENCE

Journal homepage: https://forestscience.com.ua/en
*Ukrainian Journal of Forest and Wood Science*, 15(3)

UDC 630*182
DOI: 10.31548/forest/3.2024.61

# Assessment of ecosystem services of recreational and health-improving forests in Ivano-Frankivsk Region

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**Abstract**. Optimising the interaction between society and the environment is one of the fundamental directions of recreational forest management. To improve the efficiency of using ecosystem services of recreational and health-improving forests, there is a need to develop new approaches and tools for management decision-making, a key component of which is

***Suggested Citation:***
Kyrylenko, Ya., Pelyukh, O., Parpan, T., Gudyma, V., & Holubchak, O. (2024). Assessment of ecosystem services of recreational and health-improving forests in Ivano-Frankivsk Region. *Ukrainian Journal of Forest and Wood Science*, 15(3), 61-81. doi: 10.31548/forest/3.2024.61.

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the assessment of these beneficial goods. The aim of the study is to analyse public opinion regarding the expressed and identified preferences for the characteristics of recreational forests and recreational facilities, as well as to assess the willingness to pay for preferred forest characteristics and the maintenance of recreational facilities in proper condition. The study was conducted from June to August 2022 using a direct and anonymous online survey. It was found that respondents are willing to pay an average of 1-100 UAH/year to create and maintain the preferred characteristics of the forest and 101-500 UAH/year to create and maintain recreational facilities. As for the respondents' perception of forest characteristics that affect the choice of a place to relax, preference is given to mixed forests (74.8%), in which three tree species grow (57.9%), and forests up to 20 meters high (40.2%). On the other hand, only 15.9% of respondents preferred forests taller than 20 meters. The presence of deadwood in the forest is positively perceived by 51.4% of respondents, and 10.3% do not pay attention to the presence or absence of standing dead and drying up trees in the forest. The most important needs for which respondents visit recreational forests were walks, family recreation, and observing forest landscapes. The integration of the identified perceptions and preferences regarding recreational forests and objects into innovative decision-making in the field of forestry ensures a synergy of benefits, such as increasing the attractiveness of recreational forests and forest landscapes, increasing the resilience of forests to climate change, and meeting the local demand for wood biomass

**Keywords**: forest ecosystem services; nature recreation; survey; nonparametric statistics, contingent valuation method

## Introduction

Recreational and health-improving forests play a crucial role in improving people's physical and mental health, as well as in preserving biodiversity and regulating the climate. Assessing ecosystem services will help understand their real value to society, which in turn can promote rational management of forest resources and the development of effective strategies for their conservation and use. In the structure of forest resource use, the social functions of the forest, particularly recreational, sanitary-hygienic, and cultural-aesthetic functions, play an important role. The concept of ecosystem services is an active area of interdisciplinary research, involving representatives from natural and socio-economic sciences.

According to N.Y. Vysotska *et al*. (2019) and V.P. Tkach *et al*. (2023), the total area of Ukraine's forest fund is 10.4 million hectares, of which 9.6 million hectares are covered with forest vegetation. Forests are important for biodiversity and provide a wide range of ecosystem services such as water supply, climate regulation, and recreational opportunities. However, not all forest ecosystem services are equally valued, and often, economic valuation focuses primarily on the provisioning services of forests. The economic value of roundwood trade, employment in forestry, income from secondary uses, and the value of game hunting are included in the concept of the economic value of forests. Under these conditions, recreation and ecotourism, which belong to cultural services, are not taken into account, although world forestry increasingly emphasises these intangible services and goods. Recreational and health-improving forests are the most suitable for recreation due to their proximity to settlements and low visitation costs. The area of such forests is 1,586.1 thousand hectares or 5.3% of the total forest fund of Ukraine. At the same time, all forests in Ukraine generally have recreational functions.

The non-market values of forest ecosystems are of great importance for the quality of human life, and this awareness should be reflected in the forest management process and their socially optimal use. O. Holubchak *et al*. (2019) argue that one of the main conditions for increasing the level of provision of ecosystem services by recreational and health-improving forests is a deep analysis and monitoring of their state, which will allow developing priority services on a paid basis.

The attractiveness of forest landscapes has been an object of sociological and economic research since at least the mid-20th century. Studies by J. Kamp (2022) and J. Trummer & K.T. Hegetschweiler (2023) on the preferences of recreationists show that forest characteristics directly affect their visual perception of the forest and their desire to visit a particular area. The development of modern technologies makes it possible to use various research methods, such as collecting data in social networks, mapping based on geographic information systems, and involving machine learning (Lingua *et al.*, 2023). Researchers O. Karasov *et al.* (2020) used geolocated data from social media to assess scenic values and landscape preferences. The application of geographic information systems in conjunction with social media data analysis allows for a better understanding of the relationship between landscape structure and scenic perception.

C. Lehto *et al.* (2024) used viewshed analysis and machine learning methods to identify landscape preferences among recreationists. This approach allowed for a deeper understanding of how recreationists perceive natural and cultural landscapes and what landscapes they find attractive. The results of the study open up new possibilities for planning and managing recreational areas in a way that is responsive to the preferences of recreationists.

Economic valuation of forest ecosystem services is a prerequisite for choosing the optimal solution for rational forest management, protection, and conservation. It provides a set of tools for decision-making based on the information obtained and helps to understand the benefits and consequences of interventions that affect forest ecosystems. Yu. Shtyk (2022) investigated that economic valuation should become the basis for the Ukrainian ecosystem services market. However, its functioning requires the solution of economic and legal problems that exist in the field, increasing the investment attractiveness of ecosystem services, as well as transforming the institutional structure and developing a taxation system for users of ecosystem services.

The aim of the study was to identify public perceptions and expressed preferences regarding the characteristics of recreational and health-improving forests and recreational facilities in the Ivano-Frankivsk Region. The novelty of the work was to determine the dependence of the respondents' willingness to overcome a certain distance to visit a forest based on selected characteristics (species composition, age structure, presence of standing dead trees) and the willingness to pay for the desired characteristics and the creation and maintenance of recreational facilities.

## Materials and Methods

One of the key methods for valuing ecosystem services is the indirect market valuation method, which is applied in the absence of markets for certain ecosystem products and services – the contingent valuation method. The value of the ecosystem service (in this case, recreation as a cultural service) was determined based on the results of a questionnaire survey of respondents ($n = 140$), which concerned the assessment of recreation preferences in the forests of the Ivano-Frankivsk Region. This value was reflected in the price that recreationists are willing to pay for the goods provided by the recreational area. The essence of the method involves constructing a hypothetical market and asking individuals about their willingness to pay for products and goods. The main stages of implementing the contingent valuation method were: assessment, determining the method and obtaining responses to questions or price offers, calculating average values of willingness to pay (or willingness to accept compensation), evaluating the proposed buyer's price curve, analysing the overall willingness to pay, and assessing the success of the method's application.

The contingent valuation method takes into account public preferences and makes it possible to determine the existence value, which is only partially taken into account by direct market valuation methods. Thus, the contingent valuation method is based on a scenario that describes the attributes of the products or services that should be evaluated and the conditions under which respondents must decide how much they are willing to pay for the described products or services. This method belongs to the methods of stated preference and is used to determine the value of such goods as recreation (visiting parks and forests), and conserving natural goods, the assessment of which is a challenging task.

To conduct the survey, a group of experts developed an illustrative questionnaire that consisted of 5 thematic sections (26 questions). The first thematic section consisted of 4 questions concerning visiting the forest during the past 12 months. The second section (3 questions) concerned the study of respondents' preferences regarding recreational infrastructure and the components of recreational sites, as well as their willingness to pay for the creation and maintenance of a recreational facility. In the third thematic section, respondents were asked to determine the importance of forest characteristics and to choose one of the proposed forest characteristics in 5 illustrated choice sets. In addition, two questions were posed regarding the willingness to pay (UAH/year) and the willingness to travel a distance (km) to visit a forest with the selected characteristics. The fourth section (4 questions) concerned visiting forests during and after quarantine restrictions to prevent the spread of COVID-19. The final section (8 questions) addressed respondents' data: sex, age, presence of children, education level, place of residence and work, and income. All questions were concise, understandable and realistic, which helped to minimise the time required to fill out the questionnaire and motivated the respondents to answer the questions. During the survey, ethical norms outlined in the American Sociological Association's Code of Ethics (1997) were adhered to.

The study was conducted anonymously from June to August 2022 through both face-to-face and online surveys. In total, 140 respondents were surveyed. Nine respondents provided incomplete responses. Of the 131 respondents who provided complete responses, seven were from the Kyiv Region, five were from the Lviv Region, two were from the Chernivtsi Region, nine were from other regions of Ukraine (Volyn, Kharkiv, Khmelnytskyi, Odesa, Kirovohrad, Sumy, and Rivne), and one was from Poland (Krakow). All of these respondents participated in the online survey. The remaining respondents ($n = 107$) were residents of the Ivano-Frankivsk Region. Further analysis of the responses was conducted for this sample.

The quantitative recording and analysis of questionnaire data was performed using the software package XLStat 2022. For the analysis of respondents' answers, a statistical analysis of the initial data, which characterises the socio-demographic features of the respondents, was conducted. Specifically, the following indicators were calculated: Mean, Median, Mode, Standard Deviation, Variance, Kurtosis, Skewness, Range, Minimum, and Maximum.

To study the influence of independent variables on the value of willingness to pay, econometric models are proposed. To determine the form and density of the relationship between the values of willingness to pay and the selected independent variables, correlation analysis was performed, and to determine the analytical form of the relationship between the selected independent variables and the values of willingness to pay, the parameters of the multivariate regression model were estimated using the least-squares method. The obtained regression models were checked for multicollinearity and heteroscedasticity using a graphical method, the first of which occurs under the condition of high mutual correlation of independent variables. Heteroscedasticity occurs when the variance of the residuals is variable. Otherwise, homoscedasticity takes place.

To test for statistically significant differences between groups of respondents based on sex, age, education level, and place of residence, the Pearson chi-square test (χ2 test) was applied:

$$C_P = \sqrt{\frac{\chi^2}{n+\chi^2}}, \qquad (1)$$

where $n$ is the number of observations; $\chi^2$ is the mean square dependence, which measures the discrepancy between the actual number of observations and the theoretically possible number, and is calculated using the formula:

$$\chi^2 = n\left[\sum_{i=1}^{m_1}\sum_{j=1}^{m_2}\frac{f_{ij}^2}{f_{i0} * f_{j0}}\right], \qquad (2)$$

where $f_{ij}$ is the number of observations at the intersection of the i-th row and the j-th column (the frequency of group i in group j); $f_{i0}$ and $f_{j0}$ are the marginal frequencies for characteristic *x* and characteristic *y*, respectively.

The 5-point Likert scale was used to determine the level of satisfaction with ecosystem services. Respondents could indicate how important the presence of certain infrastructure or forest characteristics was to them (1 – not important at all; 5 – very important). Respondents were also asked to express their level of satisfaction with forest services (1 – completely dissatisfied; 5 – completely satisfied).

## Results and Discussion

Respondents were asked to share their experiences of visiting forests and to describe the needs that they fulfilled during these visits. Additionally, respondents expressed their own preferences for forest ecosystem services. The duration of the interviews typically ranged from 15 to 30 minutes.

Among the respondents, 64.5% were females and 35.5% were males. Their average monthly income at the time of the survey was between 5,000 and 10,000 UAH. Half of the respondents were under 35 years old, 63% lived in cities; the majority (77%) had higher education and 5% had academic degrees. The professional activity of 56% of respondents was related to the forest; 74% of those surveyed had children, including 32% who had three or more children. All respondents visited the forest during the past 12 months. 26.2% of respondents visited the forest once every two to five months and only 9.4% of respondents visited the forest once or twice a week (Fig. 1).

Almost half of the respondents used cars (45.8%) or walked (42.1%) to the forest they wanted to visit. The remaining 12.1% of visitors used other means of transportation (Fig. 2).

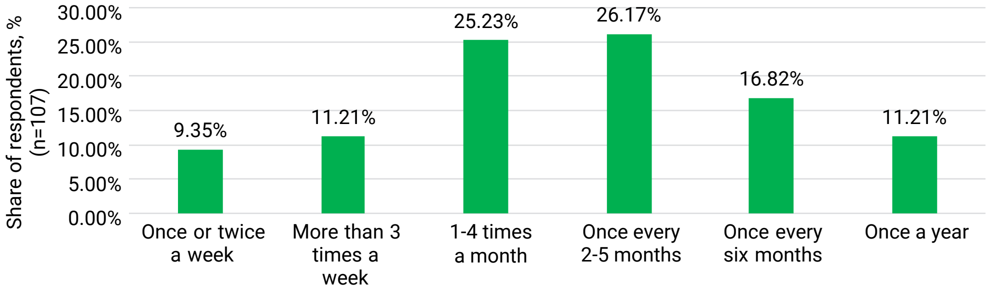

**Figure 1.** Frequency of forest visits by respondents during the research period

**Source:** compiled by the authors

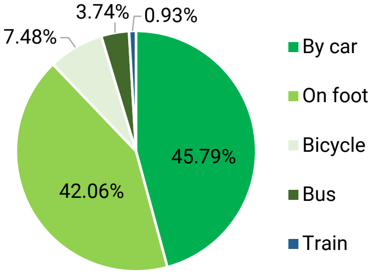

**Figure 2.** Use of different types of transport by respondents to visit the forest during the research period

**Source:** compiled by the authors

Further in the text, the results are presented using coefficients obtained on the Likert scale. Respondents indicated the following as the most important forest-related needs: family recreation (average score – 4.44), forest walks (4.33) and landscape observation – 4.20. Additionally, some respondents noted other needs as important, which were not presented in the list of options. These were primarily observing wildlife, picking berries, leisure activities, being in nature away from routine places, improving psychological well-being, clean air, walks, observing and exploring natural phenomena (Fig. 3).

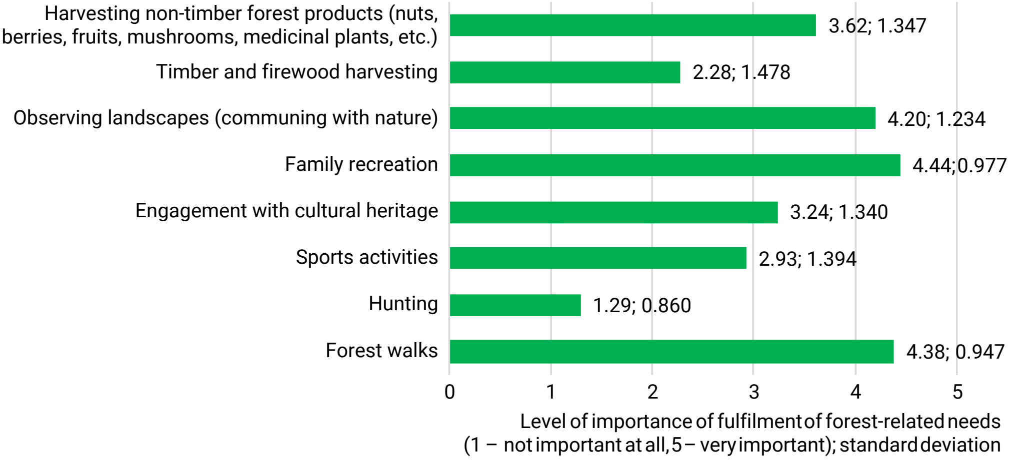

**Figure 3.** Preferences of respondents for fulfilment of forest-related needs

**Source:** compiled by the authors

According to the respondents' ratings, the most important components of recreational facilities in the forest are untouched nature and trails (average values of 4.34 and 4.26, respectively). The presence of parking lots (average value 2.97), access to sports and fitness equipment (average value 2.63), and the possibility of buying food (average value 2.49) were found to be the least important. In addition, the respondents noted that bike paths, eco-trails, benches, tables, hotels (ecological homesteads), camping sites, toilets, etc. are also important components for recreation (Fig. 4).

The most important characteristic when choosing a forest for recreation was distance (average value –3.84), while the least attention was paid to the presence and size of dead or drying up trees (average value – 2.68) (Fig. 5).

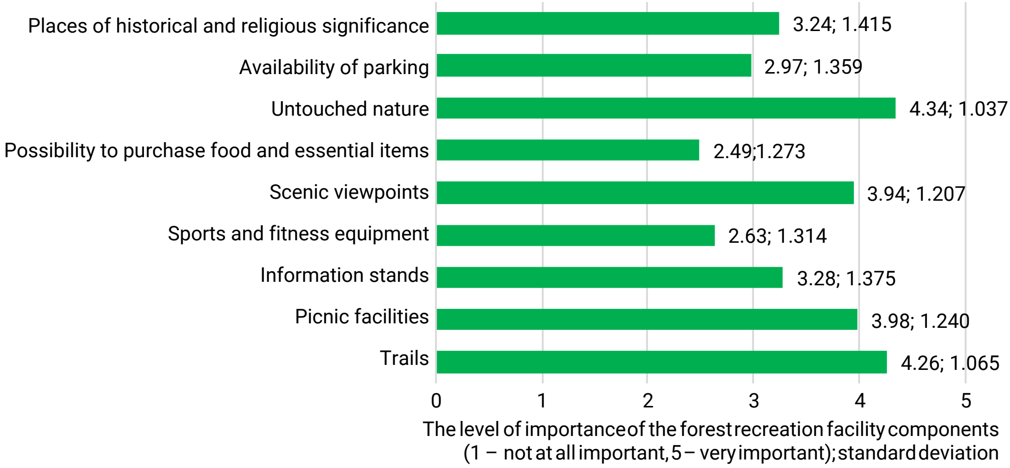

**Figure 4.** Preferences of respondents regarding the importance of recreation facility components

**Source:** compiled by the authors

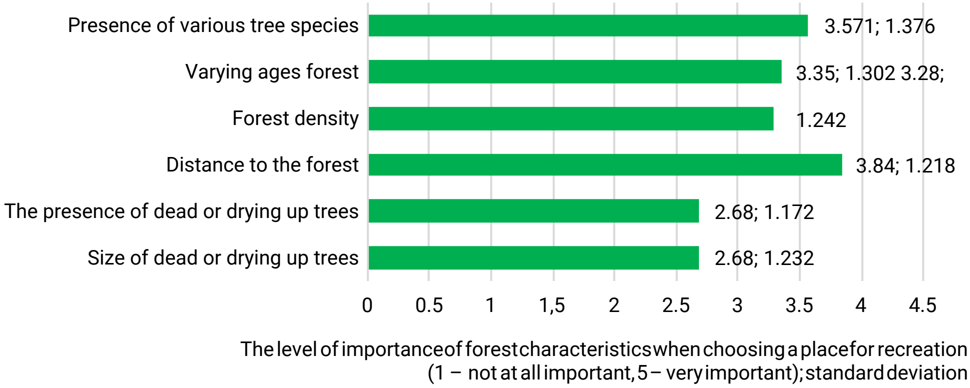

**Figure 5.** Preferences of respondents regarding the importance of forest characteristics when choosing a place for recreation

**Source:** compiled by the authors

The results of the study of the respondents' perception of forest characteristics (Table 1) showed that they prefer mixed forests (74.8%), coniferous forests (19.6%), and deciduous forests (5.6%). In terms of species composition, respondents prefer stands with three tree species (57.9%), stands with four or more species (17.8%), two species (11.2%), one species (10.3%), and for 2.8% of respondents, species composition is not important. Stands up to 10 m high were chosen by 36.4% of respondents, up to 20 m – 40.2%, more than 20 m – 15.9%, 7.5% – did not determine their preference. 69.2% of respondents preferred uneven-aged forests, 13.7% preferred even-aged forests, and 17.1% had no preference. The presence of deadwood in the forest is positively perceived by 51.4% of all respondents, and negatively by 38.3%. Among them, 43% preferred medium-sized standing dead and drying up trees (less than 40 cm in diameter), while 10.3% of respondents did not pay attention to the presence or absence of standing dead and drying up trees in the forest.

**Table 1.** Preferences of respondents regarding different forest characteristics

| **Forest characteristics** | **Share of respondents, %** |
|---|---|
| **Amount of tree species** | |
| One type of tree | 10.3 |
| Two types of trees | 11.2 |
| Three types of trees | 57.9 |
| Four types of trees | 17.8 |
| Does not matter | 2.8 |
| Total | **100** |
| **Forest composition** | |
| Coniferous (only coniferous trees) | 19.6 |
| Deciduous (only deciduous trees) | 5.6 |
| Mixed (deciduous and coniferous trees) | 74.8 |
| Does not matter | - |
| Total | **100** |
| **Tree height** | |
| Trees up to 10 metres high | 36.4 |
| Trees up to 20 metres high | 40.2 |
| Trees over 20 metres in height | 15.9 |
| Does not matter | 7.5 |
| Total | **100** |
| **Age of the trees** | |
| Trees of the same age and height | 13.7 |
| Trees of two ages and heights | 37.6 |
| Trees of different ages and heights | 31.6 |
| Does not matter | 17.1 |
| Total | **100** |
| **Presence of deadwood** | |
| There are no standing dead or drying up trees | 38.3 |
| Medium-sized standing dead and drying up trees (less than 40 cm in diameter) | 43.0 |
| Medium-sized standing dead and drying up trees (more than 40 cm in diameter) | 8.4 |
| Does not matter | 10.3 |
| Total | **100** |

**Source:** compiled by the authors

The data obtained taking into account the socio-demographic characteristics of the respondents regarding the preferences for the main characteristics of forest communities, are presented in Table 2. Statistically significant differences in preferences regarding the species composition of forests were found for different gender groups and groups based on place of residence. Respondents with a specialist diploma and those with an academic degree overwhelmingly preferred mixed forests. Respondents with incomplete higher education and a master's degree equally preferred these forests (both 75%); among those with secondary education, 37.5% preferred mixed forests. Respondents' preferences regarding the age structure of forests were found to be unequal: respondents with secondary and incomplete higher education, as well as people who lived in rural areas, preferred even-aged forests to all categories of respondents. Stands of two ages and heights were preferred by all categories of respondents, except for males and urban residents, who in most cases chose forests of varying ages and heights as the most attractive for recreation.

**Table 2.** Assessment of statistically significant differences between socio-demographic groups of respondents in terms of preferences for the main characteristics of forest communities

| **Socio-demographic characteristics of respondents** | **Forest species composition, %** | | | **χ2 test (p-value)** | **Forest age structure, %** | | | **χ2 test (p-value)** |
|---|---|---|---|---|---|---|---|---|
| | **coniferous** | **deciduous** | **mixed** | | **same age and height** | **two ages and heights** | **different ages and heights** | |
| Sex: | | | | | | | | |
| males (n = 38) | 28.95 | 7.89 | 63.16 | 4221 (p = 0.129) | 23.68 | 31.58 | 44.74 | 6532** (p = 0.038) |
| females (n = 69) | 14.49 | 4.35 | 81.16 | | 10.14 | 55.07 | 34.78 | |
| Education level: | | | | | | | | |
| secondary education (n = 8) | 37.50 | 12.50 | 50.00 | 5270 (p = 0.672) | 25.00 | 50.00 | 25.00 | 10256 (p = 0.228) |
| incomplete higher education (n = 12) | 16.67 | 8.33 | 75.00 | | 25.00 | 58.33 | 16.67 | |
| Specialist diploma (n = 2) | 0.00 | 0.00 | 100.0 | | 0.00 | 100.0 | 0.00 | |
| Master's degree (n = 80) | 20.00 | 5.00 | 75.00 | | 13.75 | 48.75 | 37.50 | |
| academic degree (n = 5) | 0.00 | 0.00 | 100.0 | | 0.00 | 100.0 | 0.00 | |
| Place of residence: | | | | | | | | |
| city (n = 40) | 16.42 | 1.49 | 82.09 | 7638** (p = 0.017) | 8.96 | 38.81 | 52.24 | 7366** (p = 0.024) |
| village (n = 67) | 25.00 | 12.50 | 62.50 | | 25.00 | 45.00 | 30.00 | |
| Total (n = 107) | 19.63 | 5.61 | 74.77 | | 13.68 | 37.61 | 31.62 | |

**Notes:** * significance level α = 0.05, ** statistically significant estimates (p-value<0.05)
**Source:** compiled by the authors

Statistically significant differences were found in the responses of gender groups (χ2 test: p = 0.038, α = 0.05) – females expressed their preferences more clearly than males regarding the age structure of forests. Statistically significant differences were also found for groups of respondents by place of residence. Respondents from urban areas more clearly expressed their preference for mixed forests (χ2 test: p = 0.17, α = 0.05). The χ2 test did not reveal statistically significant differences in the species and age structure of forests in the responses of different age groups of respondents. Most often, respondents are willing to pay (WTP) for the creation and maintenance of the desired characteristics of the forest and recreational facility up to 500 UAH/year (Fig. 6). Only 11.9% of respondents are willing to pay more than 1000 UAH/year for the creation and maintenance of a recreational facility with the desired characteristics, and 8.4% of respondents – for the creation and maintenance of the desired characteristics of the forest. 12.3% of respondents are not willing to pay at all.

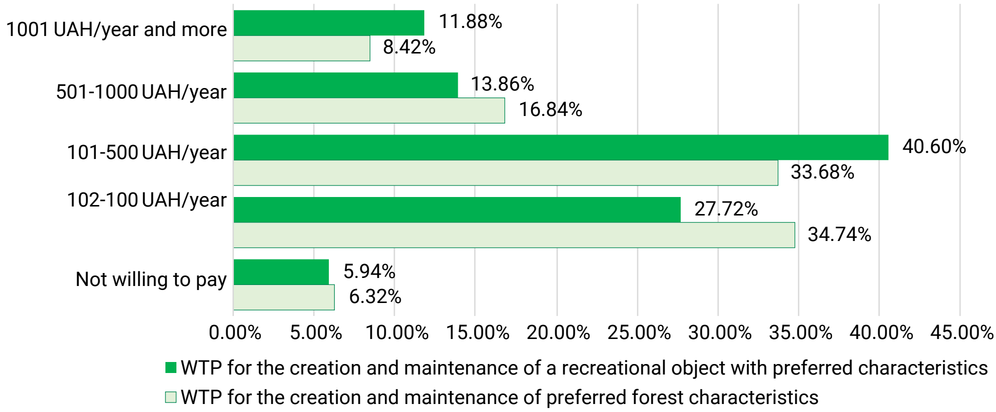

**Figure 6.** The willingness of respondents to pay for the creation and maintenance of a recreational facility and forest with the preferred characteristics

**Source:** compiled by the authors

Accordingly, in the proposed econometric model, the following factors influence the value of respondent's willingness to pay for the creation and maintenance of the desired characteristics of the forest (Y1, UAH/year) and recreational facilities (Y2, UAH/year):

- sex: 1 – male, 2 – female (X1);
- age: years (X2);
- presence of children: 1 – no, 2 – yes (X3);
- education level: 1 – no education, 2 – secondary, 3 – college, 4 – higher (X4);
- work relation to forestry: 1 – no, 2 – yes (X5);
- average monthly income: UAH/year (X6);
- place of residence: 1 – village, 2 – city (X7);
- frequency of forest visits: 1 – rarely, 2 – often, 3 – very often (X8).

A statistical analysis of the initial data is presented in Table 3. On average, respondents are willing to pay 1-100 UAH/year for the creation and maintenance of the forest according to their preferences, and 101-500 UAH/year for recreational facilities. The average age of the respondents was 39 years, and the average income was 5-10 thousand UAH/month. Among the respondents, females under the age of 35 who live in rural areas, have higher education and are mothers were the most common. Their average monthly income was 5 thousand UAH at the time of the survey, and their work was related to forestry.

**Table 3.** Statistical analysis of the initial research data

| **Indicators** | **WTP for forest creation and maintenance, coefficient 1-** | **WTP for the creation and maintenance of a recreational facility, coefficient 1-** | **Sex** | **Age, years** | **Presence of children** | **Education** | **Profession** | **Income, coefficient 1-** | **Place of residence** | **Frequency of visits** |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Y1** | **Y2** | **X1** | **X2** | **X3** | **X4** | **X5** | **X6** | **X7** | **X8** |
| Mean | 2.16 | 2.95 | 1.64 | 38.90 | 1.74 | 3.58 | 1.45 | 3.00 | 1.63 | 2.07 |
| Median | 2.00 | 3.00 | 2.00 | 37.00 | 2.00 | 4.00 | 1.00 | 3.00 | 2.00 | 2.00 |
| Mode | 3.00 | 3.00 | 2.00 | 35.00 | 2.00 | 4.00 | 1.00 | 2.00 | 2.00 | 2.00 |
| Standard deviation | 1.04 | 1.07 | 0.48 | 13.59 | 0.44 | 1.01 | 0.52 | 0.94 | 0.49 | 0.70 |
| Sample variance | 1.19 | 1.14 | 0.23 | 184.75 | 0.20 | 1.02 | 0.27 | 0.89 | 0.24 | 0.48 |
| Kurtosis ratio | -0.17 | -0.35 | -1.65 | -0.60 | -0.81 | 1.25 | -1.36 | -0.67 | -1.75 | -0.91 |
| Skewness | 0.27 | 0.33 | -0.61 | 0.38 | -1.10 | -1.54 | 0.42 | 0.41 | -0.53 | -0.10 |
| Range | 4 | 4 | 1 | 58 | 1 | 4 | 2 | 4 | 1 | 2 |
| Minimum | 1 | 1 | 1 | 18 | 1 | 1 | 1 | 1 | 1 | 1 |
| Maximum | 5 | 5 | 2 | 76 | 2 | 5 | 3 | 5 | 2 | 3 |

**Note:** willingness to pay and income are stated as of 2021-2022
**Source:** compiled by the authors

One of the statistical indicators of the obtained data is the kurtosis coefficient, which serves as a numerical characteristic of the probability distribution of a real random variable. Its negative coefficient for willingness to pay, as well as for independent variables, indicates a relatively flatter distribution. A relatively steeper distribution is observed for the dependent variable Y1 and all independent variables except X4 (education).

The asymmetry indicator characterises the deviation of the distribution from symmetry and in this study case significantly differs from zero for all independent variables (Xn = 1:8) and dependent variables (Y1 and Y2). Therefore, the distribution of values is asymmetric, which means that most respondents are willing to pay less than the average value of willingness to pay. The smallest amount that respondents are willing to pay for forest maintenance according to the desired characteristics was 0 UAH/year, the largest – 1000 and more UAH/year (in prices of 2021-2022); the youngest respondent was 18 years old, and the oldest – 76. To determine the form and density of the relationship between the values of willingness to pay and independent variables (Xi, i = 1:8), a correlation analysis was performed (Table 4, 5).

**Table 4.** Correlation coefficient values between independent variables Xi and dependent variable Y1

| Marking of the factor | Y1 | X1 | X2 | X3 | X4 | X5 | X6 | X7 | X8 |
|---|---|---|---|---|---|---|---|---|---|
| Willingness to pay, **Y1** | 1.00 | | | | | | | | |
| Sex, **X1** | -0.16 | 1.00 | | | | | | | |
| Age, **X2** | -0.21 | -0.02 | 1.00 | | | | | | |
| Presence of children, **X3** | -0.03 | -0.01 | -0.17 | 1.00 | | | | | |
| Education level, **X4** | -0.01 | 0.07 | **0.32** | -0.13 | 1.00 | | | | |
| Profession, **X5** | -0.02 | 0.00 | -0.13 | -0.08 | **-0.29** | 1.00 | | | |
| Average monthly income, **X6** | **0.30** | -0.25 | **-0.26** | 0.02 | -0.02 | 0.22 | 1.00 | | |
| Place of residence, **X7** | 0.23 | 0.04 | -0.07 | -0.06 | 0.13 | 0.12 | 0.21 | 1.00 | |
| Frequency of forest visits, **X8** | 0.06 | 0.20 | 0.16 | -0.09 | 0.11 | **0.24** | 0.06 | 0.23 | 1.00 |

**Source:** compiled by the authors

**Table 5.** Correlation coefficient values between independent variables Xi and dependent variable Y2

| Marking of the factor | Y2 | X1 | X2 | X3 | X4 | X5 | X6 | X7 | X8 |
|---|---|---|---|---|---|---|---|---|---|
| Willingness to pay, **Y1** | 1.00 | | | | | | | | |
| Sex, **X1** | -0.09 | 1.00 | | | | | | | |
| Age, **X2** | -0.23 | -0.03 | 1.00 | | | | | | |
| Presence of children, **X3** | 0.09 | 0.00 | -0.21 | 1.00 | | | | | |
| Education level, **X4** | -0.11 | 0.10 | **0.30** | -0.10 | 1.00 | | | | |
| Profession, **X5** | 0.01 | 0.00 | -0.11 | -0.10 | **-0.29** | 1.00 | | | |
| Average monthly income, **X6** | **0.28** | -0.25 | **-0.26** | 0.02 | -0.02 | 0.21 | 1.00 | | |
| Place of residence, **X7** | 0.24 | 0.03 | -0.09 | -0.02 | 0.14 | 0.07 | 0.21 | 1.00 | |
| Frequency of forest visits, **X8** | 0.09 | 0.19 | 0.12 | -0.15 | 0.04 | 0.31 | 0.08 | 0.18 | 1.00 |

**Source:** compiled by the authors

The results of the correlation analysis showed that there is a direct relationship between the value of willingness to pay (Y1) and such variables as the respondent's income (X6), type of residence (X7), and frequency of forest visits (X8), and an inverse relationship with others. The most significant relationship of the dependent variable (Y1) with the independent variable was found to be with the factor of the respondent's average monthly income (X6) $r = 0.30$. There is a moderate inverse relationship between willingness to pay (Y1) and the respondent's age (X2) and a moderate direct relationship between their place of residence (X7). Since the calculated correlation coefficients between the value of willingness to pay and such factors as sex, presence of children, education level, profession, and frequency of forest visits are close to zero, it can be stated that there is no statistically significant linear relationship between these variables.

The results of the correlation analysis showed that there is a direct relationship between the value of willingness to pay (Y2) and such variables as profession (X5), respondent income (X6), type of residence (X7), and frequency of forest visits (X8), and an inverse relationship with others. The most significant relationship of the dependent variable (Y2) with the independent variable was found to be with the respondent's income (X6): $r = 0.28$. A close relationship is also observed between the value of willingness to pay and such factors as the respondent's age (X2) and their place of residence (X7). Since the calculated correlation coefficients between the value of willingness to pay and such factors as sex, presence of children, profession, and frequency of forest visits are close to zero, it can be stated that there is no statistically significant linear relationship between these variables.

To determine the analytical form of the relationship between the eight mentioned factors and the value of willingness to pay for the creation and maintenance of preferred forest characteristics (Y1), the parameters of multivariate regression models were evaluated using the least-squares method. The obtained regression model is formulated as follows:

$$\begin{gathered} Y_1 = -0.09\text{X1} - 0.01\text{X2}\ 8\text{X8} + 2.50, \\ (-0.41)\ (-1.18)\ (0.51)\ (-1.25)\ (-1.11)\ (2.06) \\ (2.08)\ (0.51)\ (2.62) \end{gathered} \tag{3}$$

$$R^2 = 0.16;\ \text{corrected } R^2 = 0.09;\ F = 2.35$$

The regression model is statistically significant with a probability level of 0.95 since the calculated value of the Fisher-Snedecor *F*-criterion is 2.35, which is greater than the table value of the Fisher-Snedecor *F*-criterion (2.25) for a probability level of 0.95. The coefficient of determination is 0.16, which indicates that 16% of the variance of the total variance is explained by the independent variables represented in the model. Comparing the calculated and table values of the Student's *t*-criterion $t_{105;0.05} = 1.98$, the estimates of all parameters of the regression model (3) are statistically insignificant, except for the respondent's income (X6) and the type of place of residence of the respondents (X7).

To analyse the obtained regression model (3), it was checked for multicollinearity and heteroscedasticity. Multicollinearity occurs when there is a high correlation between the independent variables. In Table 4, there is a noticeable average correlation density between the presence of children (X3) and the education level of the respondents (X4): $r = 0.30$. The rest of the correlation density estimates between the independent variables are significantly lower, which is the basis for the absence of multicollinearity in the model (3). Heteroscedasticity occurs when the variance of the residuals is a variable. Otherwise, there will be homoscedasticity.

Analysis of the constructed graphs of the dependence of the square of the residuals and the independent variables of the respondent's age, education, and income revealed the instability of the variance of the residuals, which serves as the basis for further verification of the model. Heteroscedasticity was found for the obtained regression model of the study (ratio 3). Therefore, the estimates of the model parameters obtained by the least-squares method under conditions of heteroscedasticity will be unbiased and consistent but inefficient, meaning they will have large variance and, as a result, will not be *BLUE* – estimates (*best linear unbiased estimator*). The parameter estimates of the model under conditions of heteroscedasticity lead to inefficient predictions due to increased confidence intervals of the parameters and errors when using t-tests and *F*-tests. Therefore, it was necessary to remove statistically insignificant independent variables from the regression model.

Using the stepwise regression analysis method, considering the magnitude of the *t*-statistic and the *P*-value, statistically insignificant independent variables X1 (sex), X8 (frequency of forest visits), X3 (presence of children), X5 (profession), X4 (education level), and X2 (age) were removed from regression model (3). The results of the stepwise regression analysis are presented in Table 6.

**Table 6.** Results of the stepwise regression analysis

| Regression model | $F$ | $R^2$ | Corrected $R^2$ |
|---|---|---|---|
| **Y1**=-0.09X1-0.01X2+0.12X3-0.14X4-0.24X5+0.24X6+0.45X7+0.08X8+2.50,<br>(-0.41) (-1.18) (0.51) (-1.25) (-1.11) (2.06) (2.08) (0.51) (2.62) | 2.35 | 0.16 | 0.09 |
| **Y1**=-0.01X2+0.12X3-0.14X4-0.24X5+0.26X6+0.44X7+0.07X8+2.34,<br>(-1.13) (0.50) (-1.31) (-1.13) (2.30) (2.08) (0.43) (2.69) | 2.68 | 0.16 | 0.1 |
| **Y1**=-0.01X2+0.11X3-0.14X4-0.21X5+0.26X6+0.46X7+2.38,<br>(-1.08) (0.49) (-1.28) (-1.05) (2.32) (2.18) (2.76) | 3.12 | 0.16 | 0.11 |
| **Y1**=-0.01X2-0.14X4-0.23X5+0.26X6+0.45X7+2.64,<br>(-1.19) (-1.33) (-1.13) (2.33) (2.18) (3.90) | 3.73 | 0.16 | 0.12 |
| **Y1**=-0.01X2-0.11X4+0.23X6+0.44X7+2.30,<br>(-1.24) (-1.04) (2.14) (2.09) (3.79) | 4.33 | 0.15 | 0.11 |
| **Y1**=-0.01X2+0.23X6+0.40X7+2.09,<br>(-1.65) (2.11) (1.95) (3.65) | 5.40 | 0.14 | 0.11 |
| **Y1**=0.28X6+0.41X7+1.45,<br>(2.57) (2.00) (3.41) | 6.65 | 0.11 | 0.10 |

**Source:** compiled by the authors

The value of the coefficient of determination ($R^2$) of the obtained regression model is 0.11, which indicates that 11% of the variance of the willingness to pay for the creation and maintenance of preferred forest characteristics can be explained by the variance of the presence of the place of residence and the average monthly income of the respondents. The value of the $F$-criterion increased from 2.35 to 6.65, which indicates an increase in the statistical significance of the regression model. Therefore, this model can be used for analysis and forecasting with 95% confidence.

Based on the equation of the obtained regression model, it can be stated that with a probability of 95%, a change in the respondent's place of residence will increase their willingness to pay by 0.28 UAH/year; with an increase in the respondents' monthly income by 100 UAH/year, the value of their willingness to pay will increase by 41 UAH/year.

To determine the analytical form of the relationship between the eight mentioned factors and the value of willingness to pay for the creation and maintenance of p recreational facilities (Y2), the parameters of multivariate regression models were evaluated using the least-squares method. The obtained regression model is formulated as follows:

$$\begin{gathered} Y_2 = -0.37X1 - 0.02X2 + 0.20X3 - 0.03X4\text{м}- \\ - 0.38X5 + 0.28X6 + 0.46X7 + 0.20X8 + 2.93, \\ (-1.38)\ (-1.79)\ (-0.72)\ (-0.23)\ (-1.46)\ (1.97) \\ (1.74)\ (1.01)\ (2.54) \qquad (4) \\ R^2 = 0.18;\ \text{corrected } R^2 = 0.11;\ F = 2.56 \end{gathered}$$

The regression model is statistically significant with a probability level of 0.95 since the calculated value of the Fisher-Snedecor $F$-criterion is 2.56, which is greater than the table value of the Fisher-Snedecor $F$-criterion (2.25) for a probability level of 0.95. The coefficient of determination is 0.18, which indicates that 18% of the variance of the total variance is explained by the independent variables represented in the model. Comparing the calculated and table values of the Student's $t$-criterion $t_{105;0.05} = 1.98$, the estimates of all parameters of the regression model (4) are statistically insignificant.

Overall, the research results show that respondents expressed a higher preference for mixed forest stands (74.8% of all respondents), where there are three or more tree species (57.9% of all respondents). Respondents also favoured uneven-aged forests (37.6% of all respondents) and very uneven-aged forests (31.6% of respondents); the largest percentage of respondents preferred forests up to 20 meters high (40.2%). Regarding the presence of deadwood, the majority of respondents (51.4%) expressed a positive attitude towards its presence in the forest.

The applied approaches of the contingent valuation method, statistical analysis, and calculated nonparametric statistics criteria for studying the public's perception of forest plantation characteristics based on the expressed preferences of respondents allowed to identify the demand for the species and age structure of forests. In particular, the results of the Kruskal-Wallis nonparametric test showed that respondents highly value the recreational resources of the forest and consider the forest ecosystem an important element of natural capital that meets their life needs.

Statistically significant differences were found using Pearson's chi-squared test in preferences regarding the species structure of forests for respondent groups by place of residence ($\chi^2$ test: $p = 0.017$, $\alpha = 0.05$); regarding the age structure of forests for gender groups ($\chi^2$ test: $p = 0.038$, $\alpha = 0.05$) and for respondent groups by place of residence ($\chi^2$ test: $p = 0.024$, $\alpha = 0.05$). Respondents with a low level of education and living in rural areas preferred even-aged forests. Females expressed their preferences more clearly than males. Respondents with a specialist diploma and an academic degree preferred mixed forests. In general, 74.8% of respondents preferred mixed forests.

The willingness of respondents to pay for the creation and maintenance of preferred forest characteristics and recreational facilities was assessed using the correlation-regression analysis method. It was found that respondents are willing to pay an average of 1-100 UAH/year for the creation and maintenance of forests in accordance with their preferred characteristics and 101-500 UAH/year for recreational facilities. The obtained estimates of the willingness to pay for the creation and maintenance of preferred forest characteristics showed that the respondents' income and type of place of residence were statistically significant. The variance of these factors explains 11% of the variance of the willingness to pay for forest maintenance in accordance with the expressed preferences ($R^2 = 0.11$). Such factors as sex, frequency of forest visits, presence of children, connection of profession with forestry, level of education and age were found to be statistically insignificant, as well as the assessment of the willingness to pay for the creation and maintenance of recreational facilities.

The obtained results of assessing respondents' preferences regarding recreation in the forests of the Ivano-Frankivsk Region will contribute to optimising forestry measures aimed at enhancing the attractiveness of recreational forests and creating suitable conditions to meet the socio-economic needs of the population. They will also shape the necessary strategies for forestry enterprises to create recreationally appealing forests.

Economists often assess the monetary value of forest ecosystem services, although the concept of economic value is not necessarily based on monetary expression. According to researchers L.H. Goulder & D. Kennedy (1997), this cannot be done, since ecosystems and species have the right to exist regardless of whether they are used by society. The counterargument is that the inability to assess the monetary value of forest ecosystem services can lead to their depletion or even loss. The inability to determine the economic value of wildlife habitat and the value of hydrological or recreational services of forest ecosystems can lead to an "emphasis" on logging with a clearly expressed economic value – to the detriment of the unvalued ecosystem services of forests, as reflected in the work of R. Costanza *et al.* (1997). Researchers noted that studying the value of ecosystem services allows for the assessment of nature's contribution to human well-being and sustainable development. Understanding the value of natural capital promotes the rational use of resources and the preservation of biodiversity for future generations.

There are corresponding relationships between services, cost, and methods of economic valuation, which were considered by R.S. de Groot *et al.* (2002) and L.C. Braat & R. de Groot (2012). The researchers found that the classification of ecosystem services promotes the integration of the worlds of natural science and economics, conservation and development, and public and private policy. This is an initiative that aims to balance the use of natural resources with their conservation for future generations. It promotes the development of strategies that take into account the interests of all stakeholders for sustainable development.

Research by H. Wittme *et al.* (2013) and O.R. Pelyukh & L.D. Zahvoyska (2017) shows that many factors influence people's preferences for forest characteristics and, therefore, their willingness to pay for the creation and maintenance of preferred forest characteristics and recreational facilities. Different studies have identified different preferences, suggesting that they are partly shaped by cultural, regional, and socioeconomic factors. People's preferences for forest characteristics may be influenced by their membership in certain social groups (CICES – Common International Classification of Ecosystem Services, n.d.), age, sex (Babí Almenar *et al.*, 2023), and recreational activity (Millennium Ecosystem Assessment, 2005).

Among the factors influencing public preferences, ecological knowledge holds a prominent place. Psychological studies conducted by S. Pagiola *et al.* (2004) confirm that people with sufficient knowledge about forest ecosystems (people with higher education, people who often visit forests, or people who actively participate in forest management planning) are more likely to prefer visiting natural forests. In recent studies by A. Filyushkina *et al.* (2017) and V. Gundersen *et al.* (2019) regarding preferences for specific characteristics of boreal landscapes with a predominance of coniferous species, respondents preferred forests with the participation of deciduous species, the introduction of which contributed to greater forest heterogeneity, which improved recreational value. In this case, the respondents also preferred mixed forests.

Considering the results of these studies, a hypothesis is formulated regarding the form of the regression model and the nature of the relationship between the dependent and independent variables. Based on a study of the literature on the assessment of economic value, it can be assumed that the willingness to pay for the creation and maintenance of preferred forest characteristics and recreational facilities is influenced by the material well-being of the population, age, sex, education, the presence of children in the family, type of place of residence, occupation in the forestry sector and the frequency of forest visits. It can also be assumed that there is a direct relationship between the value of willingness to pay and factors such as annual income, level of education, presence of children, and age, meaning that as the values of these factors increase, the value of willingness to pay also increases.

## Conclusions

The negative impact of anthropogenic pressure and climate change on the viability and productivity of forest ecosystems of the Ukrainian Carpathians requires the development of appropriate measures for their conservation, rational use, and reproduction. It is necessary to implement innovative approaches aimed at strengthening interdisciplinary research and taking into account the value of forest ecosystem services. Based on the analysis of the theoretical foundations and methods of assessing the economic value of ecosystem services, a contingent valuation method was proposed and tested, which belongs to the methods of expressed preferences for assessing the recreational value of the forests in the Ivano-Frankivsk Region.

The results of a study of people's preferences for recreation in the forests of the Ivano-Frankivsk Region showed that the most important needs were family outings, forest walks, and landscape viewing. The most significant components for recreation in the forest were the presence of trails, and the least important were parking spaces, access to sports activities, and the possibility to buy food. The most important characteristics when choosing a forest as a recreation object were distance, and the least attention was paid to the presence and size of dead trees, or trees that are drying up.

The results of the study on the public's perception of forest characteristics showed that respondents prefer mixed forests (74.8% of respondents) where there are three or more tree species (75.7% of respondents); 2.8% of respondents indicated that the number of tree species does not matter to them. In terms of age structure, respondents prefer uneven-aged forests (69.2% of respondents). The presence of deadwood in the forest is positively perceived by 51.4% of respondents and negatively by 38.3%. However, most respondents (43%) prefer standing dead and drying up trees of medium size (less than 40 cm in diameter), and only 8.4% of respondents like large standing dead and drying up trees (more than 40 cm in diameter); 10.4% of respondents do not pay attention to the presence or absence of standing dead and drying up trees, and 7.5% to the height of the trees and 17.8% to the age of the stand.

Based on correlation-regression analysis, it was found that respondents are willing to pay an average of 1-100 UAH/year for the creation and maintenance of the forest in accordance with their preferred characteristics and 101-500 UAH/year for recreational facilities. The results of the willingness to pay for the creation and maintenance of preferred forest characteristics showed that the income of respondents and their place of residence were statistically significant. The variance of these factors explains 11% of the variance of the willingness to pay for forest management in accordance with the expressed preferences ($R^2 = 0.11$). Such components as sex, frequency of forest visits, the presence of children, occupation related to forestry, education level and age were found to be statistically insignificant. The obtained estimates of the willingness to pay for the creation and maintenance of recreational facilities were also found to be statistically insignificant. The results of the study will help to solve further tasks related to increasing the attractiveness of recreational and health-improving forests and forest landscapes.

## Acknowledgements

None.

## Conflict of Interest

None.

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**Анотація**. Оптимізація взаємодії між суспільством та навколишнім середовищем є одним із базових напрямів рекреаційного лісокористування. Для покращення ефективності використання екосистемних послуг рекреаційно-оздоровчих лісів виникла необхідність розробки новітніх підходів та інструментів для прийняття управлінських рішень, ключовою складовою яких є оцінка цих корисних благ. Метою дослідження є аналіз суспільної думки стосовно висловлених та виявлених переваг ознак рекреаційних лісів і рекреаційних об’єктів, а також оцінка готовності платити за вподобані характеристики лісу та підтримання у належному стані рекреаційних об’єктів. Дослідження проведено з червня по серпень 2022 року шляхом прямого та анонімного онлайн-опитування. Встановлено, що респонденти готові щорічно платити в середньому 1-100 грн/рік за створення і підтримання вподобаних характеристик лісу та 101-500 грн/рік за створення та підтримання рекреаційних об’єктів. Щодо сприйняття респондентами характеристик лісу, які впливають на вибір місця відпочинку перевага надається мішаним лісам (74,8 %), у складі яких зростає три деревних види (57,9 %) та лісам висотою до 20 метрів (40,2 %). Натомість лісам висотою більше 20 метрів перевагу віддали усього 15,9 % респондентів. Наявність мертвої деревини у лісі позитивно сприймають 51,4 % респондентів, а 10,3 % респондентів не звертають увагу на наявність чи відсутність сухостійних і всихаючих дерев у лісі. Найважливішими потребами задля яких респонденти відвідують рекреаційні ліси були прогулянки, відпочинок із сім'єю та споглядання лісових ландшафтів. Інтеграція виявлених уявлень та уподобань щодо рекреаційних лісів та об'єктів у інноваційне прийняття рішень у сфері лісового господарства забезпечує синергію переваг, таких як підвищення привабливості рекреаційних лісів та лісових ландшафтів, підвищення стійкості лісів до змін клімату та задоволення місцевого попиту на деревну біомасу

**Ключові слова**: послуги лісових екосистем; відпочинок на природі; опитування; непараметрична статистика; метод умовного оцінювання

Received: 29.03.2024; Revised: 12.07.2024; Accepted: 15.08.2024

UKRAINIAN JOURNAL OF FOREST AND WOOD SCIENCE

Journal homepage: https://forestscience.com.ua/en
*Ukrainian Journal of Forest and Wood Science*, 15(3)

UDC 631.811.98:630*24:582.475.4
DOI: 10.31548/forest/3.2024.82

# Growth stimulant influence on biometric indicators of oak seedlings in the Bukovyna Sub-Carpathian region

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**Abstract**. The use of growth stimulants for the cultivation of oak seedlings in the Bukovyna Sub-Carpathian region allows to accelerate their development and increase their sustainability in an environment where there is no natural forest regeneration. The aim of the study was to evaluate the effect of growth stimulants at different multiplicity of treatments during the growing season

***Suggested Citation:***

Andrusiak, Yu., Sendonin, S., Puzrina, N., Boiko, O., & Boiko, H. (2024). Growth stimulant influence on biometric indicators of oak seedlings in the Bukovyna Sub-Carpathian region. *Ukrainian Journal of Forest and Wood Science*, 15(3), 82-95. doi: 10.31548/forest/3.2024.82.

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on the biometric parameters of *Quercus robur* L. Seedlings were grown in Ecotherm containers in the glasshouse of the base nursery. The composition of the substrate for filling the containers is a mix of peat, sand and black soil in equal proportions with mycorrhiza from under the forest canopy of oak stands. The results of the effect of growth stimulants on the biometric parameters of one-year-old seedlings of common oak with a closed root system are presented. Plant growth stimulants were used for spraying and irrigation seedlings during their cultivation. The results of the research indicate a positive effect of the use of growth stimulants on the seedlings of common oak. All experimental variants showed a positive effect on the biometric parameters of one-year-old oak seedlings at three, six and nine times of feeding with growth stimulants during the growing season. The difference in the variants with the use of plant growth stimulants compared to the control in height is up to 27%, in the length of the root system – up to 43%, and in the total length – up to 29%, accordingly, depending on the dose of the stimulants and the frequency of treatment during the growing season. Refined data on the biometric parameters of one-year-old seedlings of common oak with a closed root system grown in closed ground conditions were obtained. The data obtained are useful for forest restoration in regions with damaged or degraded ecosystems where natural regeneration is limited

**Keywords**: planting material; seedling height; root system length; seedling feeding; cultivation

## Introduction

Improving the efficiency of forest plantations and preserving the forest fund are key tasks for ensuring environmental sustainability and biodiversity. Optimal methods of growing and caring for forest crops contribute to the rapid growth and health of trees, which ensures their resistance to diseases, pests and climate change. Biometric parameters of tree seedlings include growth parameters such as height, trunk diameter, number of leaves and root mass, which are important for assessing their development and adaptation to local conditions.

The reproduction methods of plantations involving common oak (artificial, natural or combined) are among the methods of plantation reproduction. According to M. Rumiantsev *et al.* (2022), the most common is artificial, i.e. the creation of forest crops. The production of *Quercus robur* L., which accounts for most hardwood plantations in the Bukovyna Sub-Carpathian region, continues to increase, which will continue to grow in the future (Tkach *et al.*, 2019), so the success of reforestation largely depends on the type and quality of planting material, which can be improved by certain growth stimulants. In Ukraine and abroad, various biologically active substances are actively used to improve the efficiency of growing planting material, in particular plant growth and development regulators (Tkaczyk *et al.*, 2022). They can significantly improve the resistance of plants to biotic and abiotic stress factors, which contributes to yield increase along with quality improvement (Raspopina *et al.*, 2022). The use of growth stimulants for growing oak seedlings is not widespread, which is confirmed by only a few scientific studies on this issue. Therefore, the studies on the influence of growth stimulants on the biometric parameters of one-year-old containerized seedlings of common oak with a closed root system in the conditions of Bukovyna Sub-Carpathian region are relevant.

The use of growth stimulants is a means of reducing the negative impact of the environment on plants to accelerate the formation of generative organs and roots, which improves important physiological processes, intensifies the hydrolysis of sugars and proteins, and activates photosynthesis. Modern plant growth regulators and other biological products consist of a complex of biologically active substances that activate metabolic processes in soil and plants, increase plant resistance to adverse conditions and contribute to the most efficient use of their productive potential. Following N. Paradikovic *et al.* (2019), growth stimulants include a variety of substances applied to the seed surface, root system or leaf surface. They can improve plant nutrition, and increase their resistance to various stresses, regardless of the supply of nutrients to plants. Modern, highly effective growth stimulants include herbal preparations, as well as humic and fulvic acids. Preparations based on amino acids, chitosan, seaweed extract, and humic substances also have high effectiveness on the plant (Lymar & Kholodnyak, 2021).

Preparations containing protein hydrolysates have an anti-stress effect on plants. In addition, they stimulate growth processes, improve the absorption and assimilation of nutrients, increase yields, and improve the development of the root system and leaf mass. Following S. Corsi *et al.* (2020), growth regulators increase plant resistance to adverse environmental conditions, such as low air and soil temperatures, significant daily temperature fluctuations, lack of moisture, negative effects of pesticides, etc.

N. Boiko *et al.* (2021) stated that all stimulants, due to the complex of biologically active substances, have high physiological activity and are capable of regulating plant growth and development. Modern growth regulators on a natural basis are safe for the environment, humans and insects, increase metabolic processes in the soil and improve its physical, chemical and biological properties.

The main components of plant growth promoters are auxin, cytokinin, gibberellin, abscisic acid and ethylene, as well as non-traditional phytohormones such as brassinosteroids, salicylic acid and jasmonic acid. Auxins are one of the most extensively studied phytohormones and are known to be involved in the regulation of growth and shape formation stimulating cell elongation and activating enzymes responsible for cell wall strength (Bilous *et al.*, 2023). According to H. Boiko *et al.* (2021), microorganisms can be potential producers of auxins, gibberellins and vitamins through the release of biologically active substances. The production of growth-stimulating substances by microbial strains can have a positive effect on the quality and quantity of seeds.

G. Benitez *et al.* (2020) determined that the complex effect of plant growth regulators on physiological, biochemical and metabolic processes in plant organisms has an anti-stress effect and unlocks the productivity potential inherent in plants. The use of growth stimulants in silviculture was studied by M. Savushchyk *et al.* (2020). They concluded that the need to use these products is determined by a decrease in the yield of high-quality planting material in nurseries as a result of prolonged pressure on the soil, especially with unjustifiably high doses of various herbicides, which reduces soil fertility.

Growth simulators are widely used in agriculture to increase the yield and quality of grain, vegetable, melon, and berry crops (Palamarchuk, 2023). However, there is little experimental data in the literature on the effect of such agents on the development of seedlings, cuttings and seedlings of woody plants. Therefore, research on the impact of promising growth stimulants and complex mineral fertilisers for growing seedlings of common oak can be used as a scientific basis for the creation of environmentally friendly and intensive technologies for growing high-quality planting material capable of withstanding plant diseases and pests in a short time.

The study aims to determine the effect of the multiplicity of treatments with growth stimulants of common oak seedlings on the biometric parameters of one-year-old containerized seedlings with a closed root system in the conditions of the Bukovyna Sub-Carpathian region.

## Materials and Methods

To assess the impact of plant growth stimulants on the quality of common oak planting material, a series of experimental plots were laid in 2023 in the greenhouse of the basic forest nursery of the State Enterprise "Hertsaiv State Specialised Forestry of the Agro-Industrial Complex" (Chernivtsi region). The influence of different concentrations of growth stimulants at different multiplicity of treatments on the seedlings of common oak was addressed.

The following growth stimulants were selected for the study: Vermibiomag NPK (Herbicom LLC, Ukraine) and Ecostim-1 (Agrosvit LLC, Ukraine). These are products are characterised by a low consumption rate, which has an optimal impact on the environment. Vermibiomag NPK is a soluble preparation with organic and mineral biogenic microelements, humic and fulvic acids, as well as biostimulants. It reduces the negative impact of stress factors, such as drought, extreme temperatures, pesticides and soil salinity and the contents of nitrites, radionuclides and heavy metals in the soil, and has the properties of a natural immunostimulant with rapid inhibition of the development of pathogens and pathogens.

Ecostim-1 with auxin complex promotes intensification and stimulation of plant growth due to the rational correlation of growth and development of plant cells and organs. The product is suitable for the treatment of plants in any conditions – from open and closed ground to hydroponic systems and can also be used for the treatment of seedlings.

The treatment of common oak seedlings was carried out for one, two and three months with the studied preparations in different doses with the addition of a growth stimulator. A total of 45 containers were selected (Fig. 1): 5 per 1 experiment variant. Vermibiomag NPK was applied in doses of 1000 ml, 2000 ml and 3000 ml per 1 ha, and Ecostim-1 – 100 ml, 200 ml and 300 ml per 1 ha with the addition of microelements at the rate of 200, 400 and 600 ml per 1 ha, respectively. One variant was used as a control (without treatment).

**Figure 1.** Containers with common oak seedlings

**Source:** authors' photo

The study used cassette trays Ecotherm (Energy Saving Technologies, Kyiv, Ukraine) for sowing seeds and obtaining planting material. The overall dimensions of the tray are 650×312×180 mm. The trays are intended for use in forest nurseries for planting seedlings of deciduous and coniferous tree species, shrubs and other planting materials. These trays are made of a special material with low moisture absorption properties. Substrate composition for filling containers: a mixture of peat in the proportions of 33.3% peat, 33.3% sand, and 33.3% black soil with mycorrhiza from under the canopy of oak trees. To obtain the desired fraction, the mixture was sieved before mixing.

For all research variants, the treatment began on June 23 with Vermibiomag NPK, 24 hours later – with Ecostim-1 solution with the addition of trace elements and was carried out every 15 days. Thus, the seedlings in trays 1, 2, and 3 were treated three times within a month, 4, 5, 6 – six times within two months, and 7, 8, 9 – nine times within three months.

After the end of the growing season, a part of the middle seedlings in each variant (control batch) was selected from the grown oak seedlings, laboratory measurements of biometric parameters (height of the aerial part, length of the root system and total length of seedlings) and the yield of standard seedlings were carried out. For an objective assessment of the effectiveness of growth stimulants during the cultivation of common oak seedlings, the average values of the control (without treatments) were addressed. They were used to compare all the indicators of the experimental seedlings. Experimental plant research complied with national and international guidelines. The standards of the Convention on Biological Diversity (1992) were used in the study. The data obtained were processed using the methods of variation statistics using the MS Excel software package.

## Results and Discussion

The results of studies on the effect of plant growth regulators on the growth characteristics of common oak seedlings are presented in Table 1.

**Table 1.** Average biometric parameters of *Quercus robur* seedlings

| **Experiment variants** | **Height of the aerial part of the seedlings, cm** | **Deviations from control, %** | **Length of the root system of seedlings, cm** | **Deviations from control, %** | **Overall length of seedlings, cm** | **Deviations from control, %** |
|---|---|---|---|---|---|---|
| **Vermibiomag NPK 0.1 ml/m², Ecostim-1 0.01 ml/m² + micronutrients 0.02 ml/m²** | | | | | | |
| Container No. 1 (triple processing) | 15.4 | +20 | 27.2 | +14 | 42.6 | +16 |
| Container No. 4 (six times processing) | 14.2 | +11 | 23.1 | -3 | 37.3 | +2 |
| Container No. 7 (nine times processing) | 14.2 | +11 | 23.9 | +0.1 | 38.1 | +4 |
| **Vermibiomag NPK 0.2 ml/m², Ecostim-1 0.02 ml/m² + micronutrients 0.04 ml/m²** | | | | | | |
| Container No. 2 (triple processing) | 13.0 | +2 | 34.1 | +43 | 47.2 | +29 |
| Container No. 5 (six times processing) | 13.3 | +4 | 21.9 | -8 | 35.2 | -4 |

*Table 1, Continued*

| **Experiment variants** | **Height of the aerial part of the seedlings, cm** | **Deviations from control, %** | **Length of the root system of seedlings, cm** | **Deviations from control, %** | **Overall length of seedlings, cm** | **Deviations from control, %** |
|---|---|---|---|---|---|---|
| Container No. 8 (nine times processing) | 14.0 | +9 | 24.0 | +1 | 38.0 | +4 |
| **Vermibiomag NPK 0.3 ml/m², Ecostim-1 0.03 ml/m² + micronutrients 0.06 ml/m²** | | | | | | |
| Container No. 3 (triple processing) | 12.5 | -2 | 26.1 | +10 | 38.6 | +5 |
| Container No. 6 (six times processing) | 14.1 | +10 | 20.4 | -14 | 34.5 | -6 |
| Container No. 9 (nine times processing) | 16.2 | +27 | 20.5 | -14 | 36.7 | +0.1 |
| Control | 12.8 | – | 23.8 | – | 36.6 | – |

**Source:** compiled by the authors

The average height of the seedlings ranged from 14.2 cm to 15.4 cm under the treatment with Vermibiomag 0.1 ml/m², Ecostim-1 0.01 ml/m² + microelements 0.02 ml/m², the length of the root system – from 23.1 cm to 27.2 cm, the total length – from 37.3 cm to 42.6 cm (Fig. 2). The best result of the application of the preparations was recorded at three treatments within 1 month (container 1). Notably, the seedlings from container 1 outperformed the control for all biometric parameters, while the six-fold (container 4) and nine-fold treatments (container 7. The growth of only the aerial part of the seedlings was stimulated, and the length of the root system was the same as in the control.

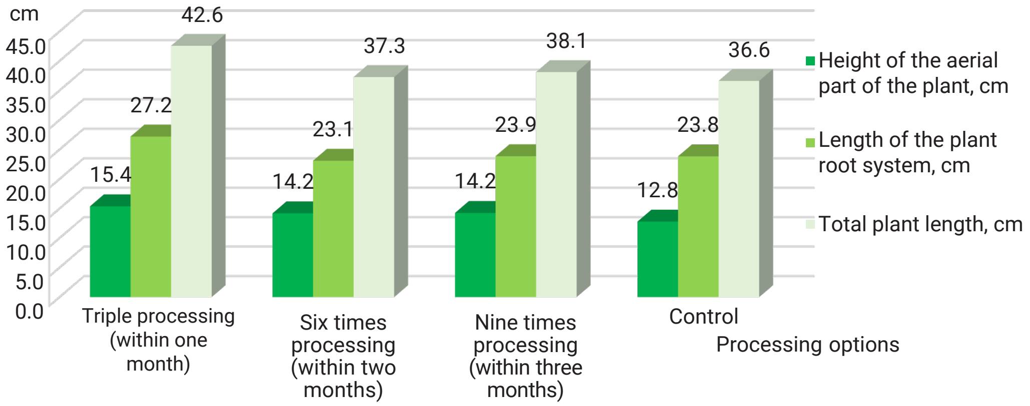

**Figure 2.** Average biometric parameters of seedlings when treated with Vermibiomag NPK 0.1 ml/m², Ecostim-1 0.01 ml/m² + microelements 0.02 ml/m²

**Source:** compiled by the authors

In general, the seedlings grown under such conditions exceeded the control by 20% in height, by 14% in root length, and by 16% in total length, respectively. All experimental variants significantly exceed the control both in height and length of the root system. A significant improvement in the overall condition of the plants, including an increase in leaf number and viability, was noted. The use of growth stimulants also contributed to a more uniform development of seedlings and increased their resistance to stressful conditions.

The average height of seedlings treated with Vermibiomag NPK 0.2 ml/m$^2$, Ecostim-1 0.02 ml/m$^2$ + microelements 0.04 ml/m$^2$ ranged from 13.0 cm to 14.0 cm, the length of the root system from 21.9 cm to 34.1 cm, and the total plant length from 35.2 cm to 47.2 cm (Fig. 3). At this concentration, three treatments within 1 month (container 2) are optimal, and at six treatments within 2 months, the total length of the seedling was less than the control (container 5). The study also noted that more frequent cultivation led to inhibition of root growth and a decrease in the overall viability of seedlings. This indicates the need for careful selection of processing modes to achieve optimal results.

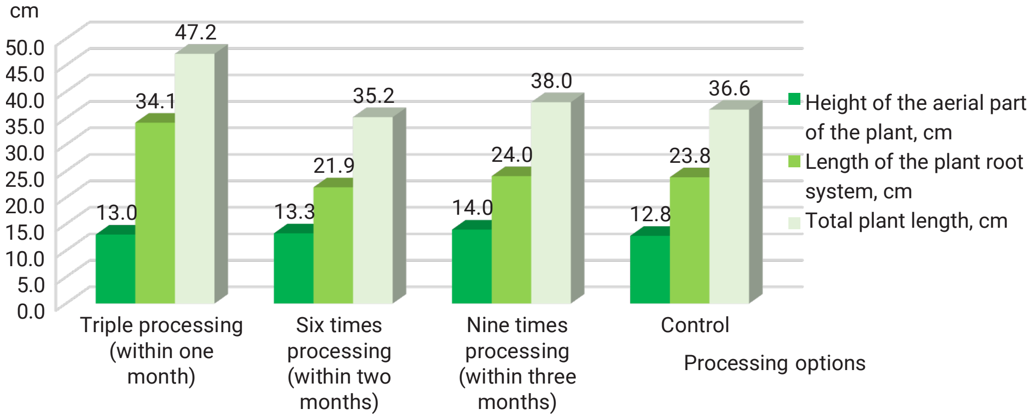

**Figure 3.** Average biometric parameters of seedlings when treated with Vermibiomag NPK 0.2 ml/m$^2$, Ecostim-1 0.02 ml/m$^2$ + microelements 0.04 ml/m$^2$

**Source:** compiled by the authors

The tested preparations had a positive effect on the growth performance of common oak seedlings. In general, the seedlings grown under the three-treatment method outperformed the control by 9% in height, 43% in root length, and 29% in total length, respectively. The biometric parameters of seedlings do not fully characterise their quality, since the viability of plants depends on the size of the assimilation apparatus. In the experimental variants using concentrations of Vermibiomag NPK 0.2 ml/m$^2$, Ecostim-1 0.02 ml/m$^2$ + microelements 0.04 ml/m$^2$, a significantly better condition of plants was observed during the cultivation of oak seedlings with the use of three times fertilisation (Fig. 4).

The average height of the seedlings under the treatment with Vermibiomag NPK 0.3 ml/m$^2$, Ecostim-1 0.03 ml/m$^2$ + microelements 0.06 ml/m$^2$ ranged from 12.5 cm to 16.2 cm, the length of the root system from 20.4 cm to 26.1 cm, the total length of the plant from 34.5 cm to 38.6 cm (Fig. 5).

**Figure 4.** The general appearance of seedlings in variants treated with Vermibiomag NPK 0.2 ml/m$^2$, Ecostim-1 0.02 ml/m$^2$ + microelements 0.04 ml/m$^2$

**Source:** authors' photo

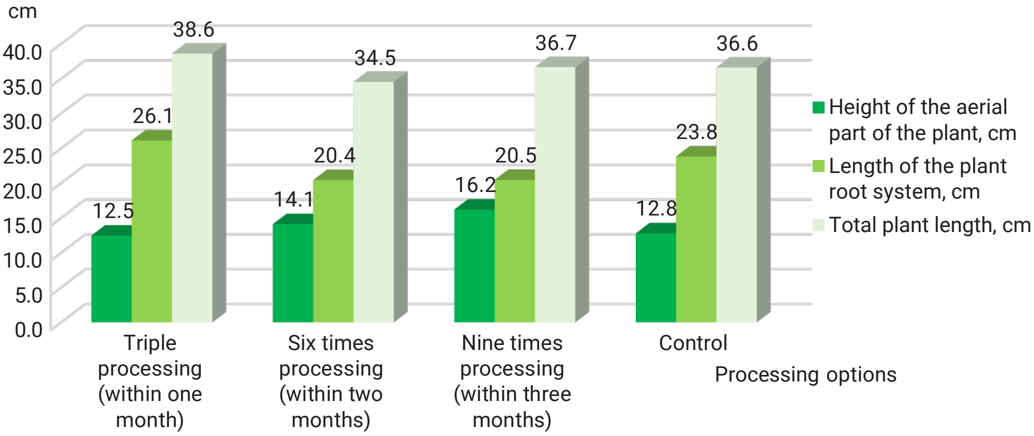

**Figure 5.** Average biometric parameters of seedlings when treated with Vermibiomag NPK 0.3 ml/m$^2$, Ecostim-1 0.03 ml/m$^2$ + microelements 0.06 ml/m$^2$

**Source:** authors' photo

In general, at this concentration, with nine treatments over 3 months, the height of the aboveground part exceeded the control by 27%, but the length of the root system was 14% shorter than the control (container 9).

The average total length of common oak seedlings is close to the control at different concentrations at six- and nine-times treatment, the best results were observed in all variants at three times treatment with Vermibiomag NPK, Ecostim-1 with the addition of microelements. Seedlings from container 2 (43%) significantly outperformed the control in terms of root length, and seedlings from containers 6 and 1 in terms of height (27% and 20%, respectively), but were significantly inferior to the control in terms of root length were seedlings from containers 6 and 9 (14%).

At the chosen concentrations, plant growth stimulants activated the growth of roots to a greater extent than the aerial part of seedlings, and according to the studies of O. Danylenko *et al.* (2021), M. Rumiantsev *et al.* (2022), plant growth regulators contribute to a more intensive increase in the mass of the aerial part and roots than in the height and diameter of the root collar of oak seedlings with a closed root system. S. Bhatla (2018) noted that plants respond to external stimuli, and feel changes in the environment, in particular temperature (Neill *et al.*, 2019). S. Fahad *et al.* (2016) noted the effectiveness of the use of growth stimulants at high temperatures, which affect plant morphology by reducing leaf area, aboveground and underground biomass, photosynthesis, and water use efficiency.

L.K. Abbott *et al.* (2018) believe that stimulants regulate many plant development processes, such as accelerating or delaying seed germination, stimulating or inhibiting shoot growth, inducing flowering and fruiting, etc. W. Rademacher (2015) studied plant growth regulators, which are important tools in modern agriculture that allow for controlling and optimising plant growth and development. They are used to improve product quality, increase yields and plant resistance to stressful conditions. Growth regulators can achieve sustainable results in the production of plant products. According to the research of several authors (Colla *et al.*, 2017; Paradikovic *et al.*, 2019), biostimulants increase the energy of seed germination, stimulate vegetation, improve the absorption and distribution of nutrients in the plant, increase the antioxidant capacity of plant tissues, increase resistance to stress factors and plant yields, and promote the rigosis of rooted cuttings during vegetative propagation. A. Pinchuk & Yu. Kosenko (2015) proved that the use of growth stimulants promotes the rooting of lignified cuttings of ornamental deciduous species, which significantly increases their survival rate and development speed. These products stimulate the formation of root hairs, improving the absorption of nutrients and water from the soil. The use of growth stimulants can help to achieve faster rooting and improve the overall quality of ornamental plants.

Thus, feeding seedlings with plant growth regulators increases their resistance and contributes to an increase in their biometric parameters compared to the control. However, it should be noted that the stimulation of seedling growth due to the influence of growth regulators sometimes occurs only after a certain period of general inhibition, and the most noticeable effect of the stimulator is observed 2-3 years after its application.

The use of growth regulators in forestry practice is driven by the decline in the production of high-quality nursery stock. This decline is attributed to signs of soil depletion and a progressive decline in fertility caused by long-term chemical exposure to the soil. This is especially true in cases of using increased doses of herbicides, which have proven to be harmful to soil biocenosis. This conclusion was reached by Yu. Taranenko (2012) and M. Savushchyk *et al.* (2020).

The use of plant growth stimulants has become a fairly common practice in the forestry sector of Ukraine when growing coniferous seedlings. This practice has been going on for about 20 years and covers different regions of the country, which is confirmed by numerous publications, such as V.A. Veshchytsky (2006) originating from Ukraine. Studies by V. Hudyma *et al.* (2014) determined a significant effect of growth stimulants on germination energy, seed germination, survival rate and biometric parameters of coniferous tree seedlings up to three years of age, compared to the control without growth stimulant treatment. V.V. Siryk *et al.* (2006) found that after treatment of Scots pine seeds with Emistim C, germination energy increased by 30-50%, and after treatment with Triman-1, germination increased by 5-37%.

O. Danylenko *et al.* (2021) proved that the most effective variants for the pre-sowing treatment of oak acorns were those in which Agrostimulin, Charcor, and Triman-1 were used. The greatest positive effect on biometric parameters and weight of one-year-old containerized seedlings during cultivation was noted in the variants where Megafol and Radifarm were used. The conducted studies evaluated the results of the use of plant growth stimulants in the cultivation of seedlings of common oak with a closed root system in open ground conditions, as well as for reforestation and afforestation. According to M. Rumiantsev *et al.* (2022), three times feeding of annual oak seedlings with a closed root system using plant growth stimulants Aminostim, Stovit TURBO, Radifarm plus, Megafol had a positive effect on their biometric parameters and general condition compared to the control (seedlings grown without the use of stimulants), which corresponds to the results of the current experiment using Vermibiomag NPK and Ecostim-1.

Therefore, to evaluate the effectiveness of growth stimulants in the cultivation of common oak seedlings, a series of experiments with different doses and frequency of treatments was conducted. The results showed that the most effective treatments were three times within a month, which contributed to a significant increase in the biometric parameters of seedlings compared to the control. The use of growth stimulants proved to be a promising tool for improving the quality of planting material in the conditions of the Bukovyna Sub-Carpathian region.

## Conclusions

The study was conducted to improve the methods of growing oak seedlings with a closed root system using growth stimulants of different concentrations at different cultivation rates and to study their effectiveness. A positive effect on the height of annual oak seedlings during cultivation with a closed root system (six and nine times feeding of seedlings with plant growth stimulants during the growing season) was noted in all experimental variants. The results of the research show that almost all experimental variants prevailed over the control of the length of the aerial part of seedlings, but the effect of stimulants on the length of the root system was less effective in the variants of Vermibiomag NPK 0.1 ml/m$^2$, Ecostim-1 0.01 ml/m$^2$ + microelements 0.02 ml/m$^2$ and Vermibiomag NPK 0.2 ml/m$^2$, Ecostim-1 0.02 ml/m$^2$ + microelements 0.04 ml/m$^2$ at six times of treatment, and concentrations of Vermibiomag NPK 0.3 ml/m$^2$, Ecostim-1 0.03 ml/m$^2$ + microelements 0.06 ml/m$^2$ – at six and nine times of treatment. According to the results obtained, the use of Vermibiomag NPK and Ecostim-1 with treatment doses of Vermibiomag NPK 0.2 ml/m$^2$, Ecostim-1 0.02 ml/m$^2$ + microelements 0.04 ml/m$^2$, respectively, and three times treatment within a month has a positive effect on growth processes in the cultivation of oak seedlings. Thus, the use of physiologically active substances allows for the regulation of vital processes in the plant organism, activates its genetic potential and increases resistance. The results obtained during the research confirm the feasibility of using the studied plant growth stimulants for growing seedlings of common oak with a closed root system in closed-ground conditions and for reforestation and forestry in the conditions of the Bukovyna Sub-Carpathian region region.

It is worth noting that the most noticeable effect of stimulants is observed several years after their application, the study of biological bases, development of new and improvement of existing technological parameters of growing common oak saplings with a closed root system using growth stimulants, which allows to obtain high-quality and sustainable planting material, is a relevant task that requires in-depth scientific research.

## Acknowledgements

None.

## Conflict of Interest

None.

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# Вплив стимуляторів росту на біометричні показники сіянців дуба в умовах Буковинського Прикарпаття

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**Анотація**. Використання стимуляторів росту для вирощування сіянців дуба в умовах Буковинського Передкарпаття дозволяє прискорити їх розвиток та підвищити стійкість у середовищі, де природне поновлення лісу відсутнє. Мета дослідження полягала в оцінці впливу стимуляторів росту за різної кратності обробок протягом вегетаційного періоду на біометричні показники сіянців *Quercus robur* L. Сіянці вирощено в контейнерах Ecotherm в теплиці базисного розсадника. Склад субстрату для заповнення контейнерів – суміш в рівних пропорціях торфу, піску та чорнозему з мікоризою з-під намету дубових деревостанів. Наведено результати впливу стимуляторів росту на біометричні показники однорічних сіянців дуба звичайного з закритою кореневою системою. Стимулятори росту рослин використовували для обприскування і поливу сходів під час вирощування сіянців. Результати дослідження вказують на позитивний вплив застосування стимуляторів росту на сіянці дуба звичайного. Усі дослідні варіанти показали позитивний вплив на біометричні показники однорічних сіянців дуба при триразовому, шестиразовому та дев'ятиразовому підживленні стимуляторами росту протягом вегетаційного періоду. Різниця у варіантах із застосуванням стимуляторів росту рослин порівняно з контролем за висотою становить до 27 %, за довжиною кореневої системи – до 43 %, та за загальною довжиною – до 29 %, відповідно, залежно від дози препаратів та кратності обробки протягом вегетаційного сезону. Отримано уточнені дані щодо біометричних показників однорічних сіянців дуба звичайного з закритою кореневою системою, вирощених в умовах закритого ґрунту. Отримані дані корисні для відновлення лісів у регіонах з пошкодженими або деградованими екосистемами, де природне поновлення є обмеженим

**Ключові слова**: садивний матеріал; висота сіянців; довжина кореневої системи; підживлення сіянців; обробіток

Received: 22.04.2024; Revised: 22.07.2024; Accepted: 15.08.2024

UKRAINIAN JOURNAL OF FOREST AND WOOD SCIENCE

Journal homepage: https://forestscience.com.ua/en
*Ukrainian Journal of Forest and Wood Science*, 15(3)

UDC 630:575
DOI: 10.31548/forest/3.2024.96

# Modern breeding methods in forestry aimed at preserving genetic diversity

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**Abstract.** This research is devoted to analysing the impact of modern breeding measures in forestry on the level of genetic diversity of forest tree species. It has been found that the main source of improved seed material for the genetic restoration of forests is base forest seed orchards. Aspects of the influence of determining factors – background pollination and the number of clones – on

***Suggested Citation:***
Sultanbaeva, V., Konurbeva, M., Osmonkanov, T., Eshimkulova, G., & Baidolotov, Sh. (2024). Modern breeding methods in forestry aimed at preserving genetic diversity. *Ukrainian Journal of Forest and Wood Science*, 15(3), 96-115. doi: 10.31548/forest/3.2024.96.

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the indicators of genetic variability of progeny have been analysed in detail. The potential of background pollination in forest seed orchards in the context of a significant decrease in the effectiveness of breeding measures and a parallel increase in the level of genetic variability of progeny has been studied. An analysis of data on the minimum number of clones in seed orchards has been carried out based on the practical experience of other developed countries. The dynamics of clone variability in terms of fertility have been investigated. The potential impact of clonal selection on the genetic diversity of tree species, particularly in reducing it, has been identified. It has been confirmed that integrating the concept of family forestry, which involves the use of vegetative propagation techniques, into the breeding strategy significantly increases the level of genetic variability in progeny. The study has demonstrated that the multiple-population breeding system provides the optimal preconditions for synergising the process of long-term intensive breeding and preserving the gene pool of tree species. It has been determined that there is no negative impact on genetic diversity from implementing a complex of optimally planned breeding programs. At the same time, the potential for intensifying the quality of gene pool conservation in the process of forest ecosystem restoration through the use of improved seed material and clones in artificial orchards has been established. Special attention is given to the maintenance of *ex situ* – valuable genetic material in forest seed production facilities, including forest seed orchards, trial cultures, and clone archives of plus trees. Research has shown that the implementation of modern innovative solutions and scientific recommendations can minimise the loss of genetic diversity in forest tree species. The results can be applied in contemporary forestry breeding programs

**Keywords**: clonal technology; somatic embryogenesis; background pollination; *ex situ*; the number of clones

## Introduction

The extensive management of forestry production processes, coupled with the destruction of forest ecosystems, the exhaustive use of technologically intensive methods to boost productivity, and the irreversible impacts of global climate change have necessitated a dynamic strategy in national forest management strategies. There is an urgent need to transition from traditional, exploitative practices towards organic, environmentally friendly approaches that ensure the preservation of genetic diversity. The creation of Kyrgyzstan's gene pool is the culmination of several generations of scientific endeavour. Targeted efforts on implementing global plant resources to enrich the republic's cultural flora have led to the creation of a genetic pool – a material and intellectual national asset that supports the republic's economic development.

Population genetic studies of forest-forming timber plants provide the theoretical foundation for breeding programs aimed at conserving, optimising, protecting, and effectively reproducing the genetic potential of species within regional contexts (Skliar *et al.*, 2020; Tykhonova *et al.*, 2021). To maintain and enhance genetic diversity during reforestation, specific population-based approaches are employed. In general, there are two primary objectives in forest management: establishing sustainable orchards that are as diverse as natural populations and producing high-quality commercial timber. To optimally achieve the first objective, plus tree selection is prioritised. This involves selecting the most productive trees within a population. The algorithm for achieving the second objective, producing high-quality timber, involves utilising the gene pool of populations or their complexes in the cultivation of artificial forests as a unified system. This systemic approach is the most promising in terms of preventing the degradation of the gene pool. Most contemporary scientists are focusing on exploring alternative technological approaches within the forestry breeding sector. These approaches aim to facilitate progress towards preserving the genetic sustainability of populations. In particular, there is a growing body of research concentrating on selection methods in forestry that prioritise the conservation of genetic diversity.

J.A. Karabaev *et al*. (2024) investigated the specific genetic components of natural systems that are subject to frequent changes in genotype due to evolutionary pressures. These pressures include genetic drift, mutation, migration, and natural selection. The researchers analysed the potential ecological risks to the adaptive capacity of biodiversity in forest ecosystems. They concluded that to mitigate the negative impacts of climate change, optimising breeding programs and implementing innovative technologies and advanced processes for preserving genetic diversity are of paramount importance. Several scientific publications by contemporary researchers have presented criteria for evaluating the effectiveness of breeding programs in forestry aimed at preserving genetic diversity. In particular, B.N. Shamshiev *et al*. (2020; 2024) focused on the effectiveness of developing sustainable forest ecosystems in Kyrgyzstan within the concept of their ecological and economic efficiency, justifying the need for implementing decarbonisation technologies and highlighting the main trends in the strategic development of the industry. Z.H. Sarymsakov & D.K. Mamadjanov (2012) studied the main types of forests in Kyrgyzstan, the status of sustainable use programs, and opportunities for optimising the situation. Genetic diversity is assessed based on the effective population size, which considers the relatedness among individuals, as well as in the context of quantitative trait variability, evaluated using mathematical statistics, and the number of alleles identified using genetic markers (Integrated management of..., 2018).

Despite significant advancements in forestry breeding within contemporary scientific communities, the question of effectively stimulating the conservation of genetic diversity remains unresolved. This problem requires further investigation and the identification of optimal solutions. The primary goal is to conduct a comprehensive analysis of the potential of modern breeding practices in forestry within the context of preserving the level of genetic diversity in forest timber tree species.

## Materials and Methods

The research utilised statistical data from the National Statistical Committee of the Kyrgyz Republic (2024), strategic programme documents, and legal frameworks within the studied sector. Specifically, the research drew upon the Concept for the development of the forestry industry of the Kyrgyz Republic for the period up to 2040 (2019), as well as the Forest Code of the Kyrgyz Republic (1999), Law of the Kyrgyz Republic No. 53 “On Environmental Protection” (1999), Law of the Kyrgyz Republic No. 18 “On Specially Protected Natural Territories” (2011), Law of the Kyrgyz Republic No. 48 “On Biosphere Territories” (1999), Law of the Kyrgyz Republic No. 53 “On the Protection and Use of the Plant World” (2001), Resolution of the Kyrgyz Republic No. 131 “On Priorities for Conservation of Biological Diversity of the Kyrgyz Republic for the Period up to 2024 and

Action Plan for Implementation of Priorities for Conservation of Biological Diversity of the Kyrgyz Republic for 2014-2020” (2014), Regulations on the State Forest Service of the Kyrgyz Republic (2002).

Based on an abstract-logical conceptual approach, the conceptual apparatus has been refined, and theoretical generalisations and conclusions have been formulated. In the course of the research, to identify the specific mechanisms of modern selection methods, methods of statistical observation, comparison, analytical-structural grouping, and forecasting were employed. Statistical observation provided summarised data that accurately reflect the characteristics of the entire set of traits of the phenomenon under study. In the course of the research, to identify the specific dynamics of the development of selection systems in forestry, a comparison was made of key indicators of qualitative changes, including the minimum number of clones in forest seed orchards (FSOs), the quality of seed material and clones in artificial stands, and the *ex situ* conservation of genetic material in forest seed production sites (FSOs, trial crops, and clone archives of plus trees).

The analytical-structural grouping method was employed to identify the specific features of modern breeding approaches and to formulate proposals for optimising the management system to create optimal conditions for increasing the efficiency and appropriateness of regional forest use systems and preserving forest gene pools. Additionally, this method was used to identify priority vectors for optimising regional forest production systems based on “green” sustainable development and sustainable decarbonisation of technological processes, thereby laying the groundwork for the active practical application of breeding technologies in the system of management of forestry activities in Kyrgyzstan. Analytical-structural grouping enabled a systematic transition from general abstract information about forestry selection technologies to the current situation in Kyrgyzstan’s forest management activities.

To identify the specific features, advantages, and effectiveness of certain decisions and approaches within the framework of the forest management selection concept, a forecasting method was used. Particular attention was paid to the need to consider potential obstacles in the practical implementation of the selection strategy. The research aims to comprehensively identify solutions in the modern forestry complex with a focus on economic efficiency and environmental safety, which, in synergy, form a system of circular sustainable economic activity in the forestry sector.

## Results

The contribution of forested areas to addressing current and future challenges in food security, poverty reduction, and environmental sustainability depends on the richness of both interspecific and intraspecific diversity of forest-forming tree species. Genetic diversity is essential for ensuring that forest-forming tree species can survive, adapt, and thrive in changing environmental conditions. It also supports the vitality of forests and provides resilience to stresses such as pests and diseases. Furthermore, genetic diversity is necessary for artificial selection, breeding, and domestication programs aimed at developing adapted varieties or strengthening beneficial traits. In many countries, the prospects for sustainable rural development will largely depend on the state of diversity within forest ecosystems and species.

The Kyrgyz Republic is characterised by relatively sparse forest cover. Forested areas in the country are represented primarily as mountain orchards with a diversity of valuable species. Nearly 90% of Kyrgyzstan’s forest ecosystems grow at altitudes between 800 and 3000 meters above sea level (National Statistical

Committee..., 2024). As stipulated by the National Forest Code, forest stands in the country serve as environmental protection areas and perform climate-regulating, sanitary-hygienic, eco-stabilising, and recreational functions. Results from practical research conducted by the Institute of Forestry at the National Academy of Sciences of Kyrgyzstan, in various natural and climatic conditions, confirm the ability of forests to mitigate the significant negative consequences of global climate change and their substantial water regulation function (Concept for the development..., 2019). The upward shift of forest ecosystems with increasing altitude potentially increases the vulnerability of many plant species to ecological and genetic impacts. The rate of climate change in the coming decades will outpace the rate at which forest ecosystems can adapt to new climatic conditions, leading to species extinction. Therefore, timely implementation of necessary forestry and selective breeding work forms the basis for preserving forest ecosystems within the concept of genetic diversity.

Research and scientific institutions in Kyrgyzstan are actively involved in modelling the potential evolution of the climatic optimum ranges for priority forest-forming tree species. A key feature of the models developed by the Institute of Water Problems at the National Academy of Sciences is the ability to dynamically track changes in the minimum altitude above sea level for juniper, common walnut, and spruce. It has been demonstrated that a 1.5°C increase in temperature stimulates fragmented upward migration, while a 4°C increase or more leads to a complete upward shift, causing a loss of ecological functions in forests (Integrated management of..., 2018). Therefore, the goal of maximising the preservation and development of forest ecosystems – selection – is consistently one of the priorities of sustainable forest management. Forest resource reproduction combines measures to ensure forest restoration, afforestation, natural regeneration, and the creation of forest orchards (Adamenko *et al.*, 2023). A comprehensive approach to researching modern breeding solutions in forestry involves emphasising the industry's specific characteristics and shaping a model to prevent the reduction of genetic diversity among timber species. Such a process is envisioned as a complex, multi-stage production system. For maximally effective management, it is necessary to consider the specific features of the economic functioning of forestry within the concept of resource potential. In this case, particular importance is attached to ensuring high-level forest resource reproduction processes.

Most forest-forming tree species are wild and are managed within natural ecosystems, or are at a very primitive stage of selection or domestication compared to agricultural crops. Forest-forming tree species are typically long-lived, highly heterozygous organisms with well-developed natural mechanisms for maintaining high levels of intraspecific variation, such as high-speed distant crossbreeding and widespread dispersal of pollen and seed. These mechanisms, combined with native environments that often vary in time and space, contribute to the evolution of forest-forming trees into some of the most genetically variable organisms on Earth. Achieving sustainable forest management is anticipated to be possible through the implementation of closed-loop forestry technologies that utilise all available resource regeneration algorithms, employing organisational, production, socio-economic, ecological, and social factors. In particular, to reduce the risk of losing part of the genetic diversity, the introduction of a stabilisation period is deemed appropriate. The latter represents a specific time frame necessary for the implementation of a full set of compensatory measures to mitigate the destructive consequences of long-term extensive forest management. The described strategy requires significant time and financial investments but is considered a necessary step for organic forestry production.

Climate change is impacting the resilience of ecosystems, which is particularly evident in the transition from traditional forestry to regenerative forestry. A reliable preventive measure to reduce the loss of genetic diversity in forest ecosystems is the creation of ecological buffer zones of 10%, which will help restore and preserve biodiversity (Salgotra & Chauhan, 2023). Additionally, the use of specialised selection methods is a necessary technological approach. All modern forest selection methods are based on:

1. The method of selecting the best plants for further propagation and use. This method falls under the category of analytical selection, where nothing new is created; instead, the best individuals from existing populations are utilised. Through intensive selection, it is possible to identify the best ecotypes, forms, and other variants within existing stands, as well as the best (plus trees), which can then be propagated and used in forestry seed production and afforestation to improve the quality of forests.

2. Hybridisation is an important selection method that enables the development of new forms and even species with a range of valuable traits and properties.

3. Polyploidy is a method of creating new plant forms by increasing the number of chromosomes several times beyond their haploid number.

4. Mutagenesis is a selection method that produces new plant forms through the application of various mutagens.

These methods are part of synthetic selection, which allows for the creation of new genetic material combinations and the construction of novel hereditary material combinations using various techniques. Following the National Development Strategy of the Kyrgyz Republic, the long-term development of the country should be framed within the concept of preserving unique natural ecosystems. The strategy aims to intensify the expansion of forest ecosystems, ensure the economic stability of the Republic's forestry sector, optimise the management paradigm for forests, and digitalise forestry infrastructure.

Forest ecosystems play a crucial role in mitigating adverse climate dynamics (Hoban *et al.*, 2021). Forests are considered the most effective natural way to regulate greenhouse gas concentrations in the atmosphere, highlighting the need to maximally preserve the species and genetic diversity of timber species in the forests of Kyrgyzstan, which function under the Republic's rather challenging climatic conditions (Table 1).

**Table 1.** Carbon stock in the forests of the Kyrgyz Republic

| No. | Category | Forest lands | Other forest lands | Total |
|---|---|---|---|---|
| 1 | Above-ground carbon stock, million tonnes | 13.3 | 0.3 | 13.6 |
| 2 | Below-ground carbon stock, million tonnes | 4 | 0.4 | 4.4 |
| 3 | Carbon stock in dead plants, million tonnes | 0.071 | 0.001 | 0.072 |
| 4 | Carbon stock in forest floor, million tonnes | 16.5 | 8.6 | 25.1 |
| 5 | Carbon stock in soil, million tonnes | 1,161 | 967 | 2,128 |
|  | Total | 1,194.9 | 976.3 | 2,171.2 |

**Source:** Concept for the development of the forestry industry of the Kyrgyz Republic for the period up to 2040 (2019)

Forest diversification can be a powerful tool in the fight against climate change. Mixed forests accumulate carbon more rapidly than monocultures, meaning they can help achieve emissions reduction goals faster. The concept of carbon offsetting through forests is based on the idea that forests act as carbon sinks, absorbing and storing $CO_2$ from the atmosphere through photosynthesis. By conserving existing forests or restoring degraded areas, the amount of carbon stored in trees and soil can be increased, effectively offsetting emissions from other sources. As the data in Table 1 shows, the carbon stock of Kyrgyzstan's forests exceeds two million tonnes. There is a need to continue ensuring the ecological balance of forest ecosystems and preserving biodiversity. Kyrgyzstan's forest ecosystems are primarily represented by spruce, nut-bearing, floodplain, and juniper forests (Fig. 1).

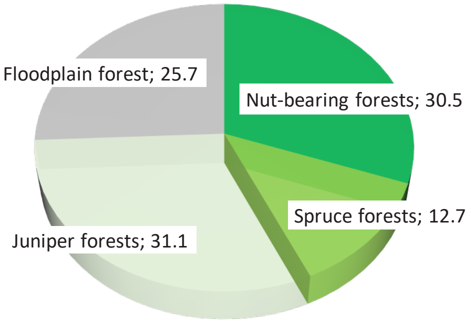

**Figure 1.** Forests of the Kyrgyz Republic as of 2023, %

**Source:** National Statistical Committee of the Kyrgyz Republic (2024)

Despite the identified challenges in this research area, optimising forest management in Kyrgyzstan within the context of preserving genetic biodiversity has significant potential that can be fully realised with strong international support and investment opportunities. The market-driven environment dictates that increasing profitability is the primary goal of forest management; therefore, the productive development of the selection sector to preserve genetic diversity is contingent upon maintaining adequate levels of economic performance (Cortés *et al.*, 2020). An adaptive forest management system aligned with the goals of sustainable development consists of a set of specific requirements, opportunities, and principles, as well as tools and technologies that contribute to enhancing the competitiveness of the sector and optimal resource utilisation.

Essential components of a sustainable development strategy for Kyrgyzstan's forestry sector, designed to maximally preserve genetic diversity, as proposed in the Concept for the development of the forestry industry of the Kyrgyz Republic for the period up to 2040 (2019), are considered to be the following:

- adapted progressive national scientific and legislative frameworks, the implementation of successful international experience and innovative solutions, as well as modelling and forecasting of dynamic situations;
- a technical and technological basis, which should allow for full analysis of information and statistical data, and integration of the latest technologies and concepts into the sector;
- a human resources basis that is aware of local needs and that makes the best use of regional potential to maximise development.

Innovative selection technologies in forestry involve identifying reliable characteristics of forest ecosystems, creating digital maps, and utilising GPS systems. A distinguishing feature of modern technologies is the active manipulation of plants at different stages of their growth cycle through a sequence of biological and technological treatments, which inevitably impacts productivity and efficiency in the forestry industry. Addressing the challenge of preventing genetic diversity loss requires preliminary data collection and analysis, the creation of digital field maps, an effective decision-making system, and the development of technologies for forest management processes.

Geographic Information Systems (GIS) are currently positioned as the most effective tool for understanding and describing dynamic geographic environments. These systems find wide application in addressing many challenges associated with using spatially distributed information to ensure environmental safety and sustainable development of territories. GIS can be effectively used for analysing ecological and landscape monitoring data, creating digital maps, and assessing the dynamics and forecasting future trends in regional land use. GIS is a complex, multi-component system, a distinctive feature of which is the application of specific methods for analysing spatial data. These methods, in synergy with activities related to the formation, accumulation, processing, and presentation of spatially coordinated information, form the fundamental basis of GIS technology. One result of such integration is the emergence of geographic information mapping, which is an automated information and cartographic modelling of natural and socio-economic geosystems based on GIS and corresponding databases.

The use of GIS is associated with the enhancement of spatial-analytical operations in eco-landscape management for biodiversity conservation in forest areas, particularly buffer zones. Buffer zones in this context can include protective zones, sanitary protection zones, restricted zones, epidemiological zones, and others. Modern GIS tools allow for the automatic generation of buffer zones around objects of any type. Network analysis, aimed at defining three-dimensional spatial models, is also a popular aspect of GIS application in forest ecosystem management. Therefore, it can be asserted that the use of geographic information technologies in the development and implementation of forest breeding programs allows for the effective evaluation of parameters in real-time, while simultaneously enabling predictive analytics. An advantage of using GIS in this context is the ability to integrate statistical methods, geographic information and digital modelling, and business graphics, which collectively allow for the identification of specific types of information as a basis for management decisions.

The integration and unification of diverse spatial information is achieved through GIS using data aggregation, conceptual communication, and extrapolation of processing results. The information processed in this way forms models of objects in the form of thematic maps, digital models of dynamics, vector images, and three-dimensional models, which significantly simplifies and optimises the selection process. A decrease in genetic variability compared to natural ecosystems is characteristic, as confirmed by numerous studies using biochemical and molecular genetics methods (Nonić & Šijačić-Nikolić, 2021). An assessment of changes in basic genetic indicators through special modelling of successive thinning in experimental cultures demonstrated a lack of negative dynamics in the concept of genetic diversity, even in the case of significant thinning intensity.

The population structure of forest species, shaped over a long evolutionary process, represents the most advantageous survival strategy for the species. Given that the population is its foundation, preserving the existing structural organisation of the species is positioned as preserving specific conditions for the self-reproduction of each population across generations. One of these conditions is the preservation of natural genetic variability within populations. To ensure genetic variability, it is necessary, based on modelling the population-chorological structure of a forest species, to identify at least one genetic reserve in each population. Given that a population is an adapted and integrated dynamic system of individuals, the applied selection systems must ensure not only the preservation of all the diversity of these genotypes and their balance in a natural state but also the maintenance of the population's capacity for natural self-reproduction during exploitation and subsequent restoration (Mero *et al.*, 2023). Forestry selection programs, in general, should combine the following selection measures:

- developing a variety model optimal for a specific cultivation zone and target purpose;
- analysing and conducting detailed comparative studies of the original natural material and its artificially produced analogue for selection;
- choosing a selection method to obtain new forms of timber forest species;
- studying the progeny obtained, followed by the selection of samples that best meet the goals of the selection process;
- initial multiplication of the selected material;
- testing in various external conditions and different ecological settings;
- state zoning of the best varieties.

Forest regeneration should primarily occur naturally. To maximally preserve the genetic diversity of forest species populations, optimised breeding programs are also necessary. It is important to note that breeding programs based on individual selection should be carried out on a limited scale, using intensive forestry techniques in the most optimal site conditions for the species. A crucial aspect of artificial forest regeneration is the use of selected seeds only in areas where stands of at least site yield classes I-II previously grew. This approach allows for the optimisation of the ratio of areas restored through natural regeneration, increases the efficiency of the selection process, ensures the maximum preservation of the natural genetic diversity of the species, and enhances the productivity and resilience of forest ecosystems to adverse environmental factors. A priority in conserving the gene pool is to ensure optimal genetic variability in forest-forming timber species to enable adaptation to dynamic environmental conditions. Variability is also essential for the success of long-term breeding programs. In particular, it is crucial to maintain a high level of genetic diversity, which is fundamentally the determining factor in a tree's breeding value.

In most developed countries, the process of tree breeding actively uses reproductive material with pre-improved characteristics (Concept for the development..., 2019). The aim is to regenerate and conserve forest crops. A breeding population represents the concept of creating a collection of trees designed to pass on genetic improvements to subsequent generations. A breeding population is essentially a group of elite trees whose direct seed or clonal progeny are actively used to establish FSOs. These FSOs, in turn, supply seed material to specific regions. Genetic optimisation in terms of growth rate, obtained from first-generation FSOs, is achieved through modern selection technologies involving crosses between unrelated trees in these FSOs (Kang, 2020). FSOs primarily consist of clonal progeny from a select group of plus trees. Genetic diversity directly depends on the number of plus trees used. The traditional approach assumes equal representation of ramets in each clone. The variability between clones in terms of pollen and seed productivity causes an uneven contribution of clones to the overall pool of gametes in the FSOs (Donazzolo *et al.*, 2020).

Forest-forming coniferous species produce vast quantities of pollen that can be carried over significant distances by wind. Background pollination is typically viewed as a negative phenomenon, as it can reduce the effectiveness of selective breeding (Shahini *et al.*, 2023). However, the introduction of new genes through this process can increase the genetic diversity of progeny. The main advantage of clonal forestry is expected to be significant genetic optimisation in terms of growth, achieving up to 25% for coniferous species and around 50% for deciduous species (Silva *et al.*, 2020). Due to the biological characteristics of these species, it is possible to obtain approximately 50-100 rooted cuttings from a single donor plant (Cobo-Simón *et al.*, 2020). Consequently, commercial clonal propagation systems require a continuous influx of new donor plants to maintain optimal levels of genetic diversity in clonal orchards.

The most effective approach to population-based selection involves ensuring a balance between productivity and species diversity during forest regeneration. The primary challenge lies in the fact that the most productive stands often lack sufficient genetic variability, while genetically polymorphic populations frequently exhibit low forestry value and productivity. In this context, the most successful approach is to select within population formations that exhibit a balanced combination of diversity, productivity, and resilience. To address this challenge, the following fundamental approaches are employed:

- a “non-random” sampling system based on the principle of “best stands and trees from the best”;
- comprehensive analysis of variability and productivity at various hierarchical levels (population, individual, gene, chromosome);
- index (rating) system for data summarisation and comparison of stands based on various indicators;
- a balanced combination of diversity, productivity, and resilience.

Forestry breeding methods aimed at preserving genetic diversity should facilitate a balance between productivity and sustainability. The proposed concept involves a systematic approach that allows for the identification of stands within specific populations that are of the highest value from both a forestry and genetic perspective. The concept involves the use of vegetative propagation techniques, and the process of reproducing forest ecosystems using improved seed material and clones in artificial orchards. Special attention is given to maintaining valuable genetic material *ex situ* within forest seed production facilities, including FSOs, trial cultures, and clone archives of plus trees. Additionally, the feasibility of creating interpopulation hybrid seed orchards should be emphasised.

Genetic diversity is the foundation of biological stability; it enables species to adapt to changing conditions, including the impacts of climate change and emerging diseases. It is the foundation for current and future breeding programs and the development of new cultivars. In addition to their invaluable contribution to ecological sustainability, forest genetic reserves (FGRs) provide a direct source of food for humans and animals, even during periods of poor harvests of annual crops. Inventorying, description of characteristic features, and monitoring are necessary to gain the knowledge required for a proper understanding of trends in the state of FGRs, which allows for informed decision-making in the area of sustainable management and the rational use of FGRs. *Ex situ* conservation is the most common conservation practice because most forest-forming tree species grow in the wild and are not domesticated. It also allows populations of species to continue to exist under the influence of evolutionary processes.

One of the promising methods for genetic improvement in forestry is intraspecific and interspecific hybridisation. An additional benefit of this method is often the heterosis effect in terms of growth rate, vigour, and even yield (Rajora & Zinck, 2021). Furthermore, among breeding technologies, it is necessary to highlight the approach focused on new sets of genetic traits, differentiation of hybrid generations based on wood quality, disease resistance, and adaptability to adverse weather conditions. Quite often, hybridisation of suitable species creates optimal conditions for the mass production of high-yielding and fast-growing hybrids, which can be actively used in forest management systems. The optimal method for creating new hybrid tree varieties is the synergy of artificial hybridisation and subsequent selection in later generations. Interpopulation hybridisation to preserve and develop the gene pool and species diversity is implemented through the method of genotype convergence, which ensures the artificial restoration of gene combinations (Ahmar *et al.*, 2021).

To effectively preserve genetic potential in forestry, it is advisable to use biotechnological procedures involving the mass propagation of timber plants. The development of vegetative propagation procedures aimed at mass replication of valuable genetic traits in progeny allows for an intensification of breeding efficiency. The testing of vegetative propagation methods demonstrates a significant reduction in costs, contributes to an increase in the volume of planting material, and intensifies the propagation of valuable hybrids, forms, and cultivars, the original material of which is often represented by single specimens. A priority principle in the forest breeding practices of developed countries, such as Sweden, which has demonstrated the highest efficiency, is the implementation of individualised breeding programs for the optimisation and conservation of the gene pool of each forest-forming species. A differentiated strategy has several advantages, including the consideration of differences between timber species, natural climatic and site conditions, and the population structure of each species. The proposed concept defines a promising task for the development of breeding programs by research and forestry organisations in Kyrgyzstan.

A thorough review of the state of forest breeding programs in Sweden at the beginning of the 1990s was conducted by Ö. Danell (1991). The researcher proposes an algorithm for a long-term breeding strategy in forestry that has demonstrated significant effectiveness. The initial source of selection-improved reproductive material of known origin is plus trees selected from natural stands. Forest seed orchards were established from cuttings taken from these trees (Fig. 2).

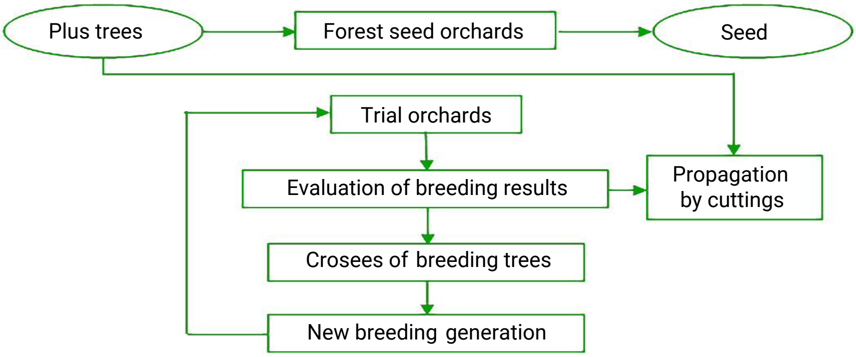

**Figure 2.** Forest selection scheme in Sweden

**Source:** M. Nonić & M. Šijačić-Nikolić (2021)

Concurrently, a significant number of experimental orchards were established in Sweden, including about 1000 trial plots across the country. As shown in Figure 2, the breeding work began with the selection of plus trees, from which first-generation forest seed orchards were created. Simultaneously, test orchards were established from seeds of plus trees. After evaluation of the testing, cuttings from the best trees were used to create second-generation FSOs. Crosses were made between trees to obtain a new generation, which also underwent field testing. Seeds and vegetative material were obtained from the best variants. By the early 1990s, Sweden had selected the following numbers of plus trees and promising clones for four main species: *Pinus sylvestris* – 6800 plus trees; *Picea abies* – 5600 plus trees + ~13000 clones; *Pinus contorta* – 200 plus trees + 1200 families; *Betula* spp. – 1450 plus trees (Danell, 1991). In each seed zone of Sweden, 600 plus trees of a particular species were tested. As a result of the testing, the 50 best plus trees were selected and used for further breeding and the creation of the next generation of FSOs.

As demonstrated by Sweden's successful experience, the optimal management of forest use and regeneration of forest ecosystems requires the development of breeding programs, both for individual forest timber plants and for their communities. Such programs should include:

◆ development of an ideal variety or selectively improved material;

◆ selecting existing or developing new breeding methods;

◆ studying, collecting, and preserving the original material for breeding;

◆ obtaining varietal or selectively improved material for regional needs and creating specialised orchards for various purposes;

◆ field trials;

◆ variety testing and zoning of the most valuable selections;

◆ using promising propagation methods and other provisions that take into account the characteristics of the forest timber species used, the natural and economic conditions of the regions, and their development prospects.

Implementing environmental innovations in forest breeding practices will ensure the long-term measurement of competitiveness and the formation of a climate-safe operating environment for forest enterprises. Typically, the process of innovation is aimed at preventing and mitigating environmental impacts while simultaneously maximising profits. A priority vector for optimising the forest management system is the formation of vertically integrated associations of environmentally oriented economic entities, which should potentially include producers of ecological raw materials, final products, and providers of energy-efficient, resource-saving, and environmentally safe selection technologies. Particular attention should be paid to establishing an effective system for monitoring and evaluating the efficiency of implemented technologies and measures within the framework of the innovative environmental development concept.

## Discussion

Most contemporary scientists whose research focus is on forest breeding technologies, which could ensure progress towards the preservation of genetically sustainable populations, confirm the extremely negative impact of depleting traditional forestry practices on the environment, especially given the intense negative dynamics of the climate.

For example, scientists H. Rachmat *et al*. (2020) argue that modernising forestry involves a phased transition from traditional to high-tech production while implementing principles of sustainable development. Through this research, scientists have proven that a nursery is a way to conserve species by collecting seedlings. In this study, many seedlings were collected to support the conservation and management of genetic resources of certain species. More than 60% of the collected species were endangered and were conserved *ex situ* and maintained in good condition through the nursery. The scientists propose developing the nursery as a place to collect a variety of species, which would save space and allow for the collection of more individuals. The researchers' development is of practical interest to Kyrgyzstan and is foreseen as an effective methodological approach for organising breeding work.

Most contemporary scientists, particularly N. Isabel *et al*. (2020), position breeding technologies in forestry as the foundation for preserving genetic diversity. These technologies are synergistic with decarbonisation technologies and sustainable development priorities, ensuring the regeneration of the resource potential of the forestry sector amidst the shift towards a circular, renewable, and sustainable economy. The precise phenotyping proposed by the scientists opens up new avenues of research that can help address specific issues, such as resistance to biotic and abiotic stress. To minimise redundant storage, optimise data queries, and keep pace with technological advancements, the authors advocate for the significant benefits of developing cyberinfrastructures that support all aspects of the data lifecycle, from acquisition to storage, integration, and visualisation. The researchers' findings suggest that the level of eco-modernisation in forestry approaches serves as an indicator of the effectiveness of applying scientific research and development. At the same time, one could argue with the scientists about the ease of implementing cyberinfrastructures. Their implementation and support require significant improvements in practices in the areas of data standardisation, ontology, analytics, and integrated databases.

Continuing this line of thought, the differentiated approach to breeding optimisation and gene pool conservation programs for each tree species, proposed as a priority in the current research, receives positive reviews in the studies of contemporary scientists. For example, D. O'Brien *et al*. (2022) are convinced that the number of clones in the selection process does not serve as a characteristic of the gene pool if there are differences in the number of ramets within clones and their seed productivity. The researchers propose a statistical model to determine the optimal number of clones in FSOs for several coniferous species. Moreover, the model considers the influence of key conditions, particularly fertility and background pollination. At the same time, scientists N. Dinato *et al*. (2020), and S. Aitken (2021) argue in favour of the expediency of individualising breeding programs in forestry to achieve maximum efficiency.

Recent studies by H. Gaisberger *et al*. (2020) and M. Vivas *et al*. (2020) demonstrate a smaller time gap between selection and implementation of results in the case of vegetative propagation, compared to the process of establishing FSOs and producing seed material. Researchers argue that the proposed method produces a limited number of clones, and the resulting timber exhibits greater uniformity.

At the same time, Y. Yin *et al*. (2021) draw attention to the fact that monoculture orchards possess the effect of maximum genetic optimisation, simultaneously increasing the risk of losing genetic diversity. Transgenic technology is increasingly used in forest tree breeding to overcome the shortcomings of traditional breeding methods, such as a long breeding cycle, complex cultivation environment, and complex procedures. According to the authors, through the introduction of exogenous DNA, genes tightly related or contributed to ideal traits, including resistance to insects, diseases, and herbicides, have been transferred to various forest trees. It is worth disagreeing with the conclusions of the scientists regarding the potentially low efficiency of transformation. It may hinder the cultivation of genetically modified trees and the identification of molecular-genetic mechanisms in forest trees compared to annual herbaceous plants (Yanitskyi, 2024).

Forest geneticists B. Vinceti *et al*. (2020) developed a multiple-population selection system that allows for the synergy of conserving the gene pool of timber species with intensive long-term selection. A survey conducted by the researchers demonstrated a positive attitude among respondents towards the use of forest reproductive material that is foreign to the planting site to better match predicted future climatic conditions, by introducing either a new local tree species or a new non-local genotype of an already planted species (while maintaining the same). At the same time, in the context of Kyrgyzstan, forest management authorities will require more evidence of the potential benefits of active adaptation and management to mitigate the impacts of climate change. Financial incentives at the state level are expected to be effective in achieving these goals.

In many contemporary scientific research, particularly those of J. Amaral *et al*. (2020) and S. Singer *et al*. (2021), the concept of somatic embryogenesis is being developed. The authors argue that it is possible to obtain a virtually unlimited number of genetic copies from embryogenic cell lines using this method. The scientists consider the supposed "risks" in the context of plant breeding as a whole, comparing the frequencies of spontaneous mutations with those (both expected and unpredictable) that occur through various conventional and biotechnological approaches to breeding, including transgenesis and genome editing. It is necessary to suggest, in addition to the scientists' conclusions, that global regulatory asynchrony surrounding genetically modified crops should be taken into account, which would allow for a more complete anticipation of associated risks.

Research into somatic embryogenesis forms the foundation of a strategy for family forest management with vegetative propagation, where seeds for somatic embryogenesis are obtained from controlled crosses of plus trees. In a review article by D. Borthakur *et al*. (2022), the potential risks of undesirable disruptions were demonstrated in some cases, while at the same time emphasising the absence of deviations in the phenotype and growth of plants. Overall, the proposals of scientists in the concept of modern breeding measures in forestry for the conservation of genetic diversity indicate the promise of the concept proposed in the current study. At the same time, maintaining the genetic heterogeneity of Kyrgyzstan's forests requires the use of breeding and genetic methods based on a population approach.

In the research of E. Enfissi *et al*. (2021), it is noted that the primary task of developing breeding technologies in forestry is to form stable forest ecosystems that can mitigate the negative impacts of climate change and the risks of biodiversity loss. The scientist analyses the component-functional structure of a typical algorithm for environmentally safe forest management, noting the expediency of using the technological potential of innovative breeding strategies and updating the need for intensive industry investment. It is difficult to disagree with the author. It should be added that the concept of renewability is now seen as a key element of sustainable forest complexes, ensuring an adequate level of regeneration of natural environment components, which can function effectively without requiring significant financial subsidies. Numerous scientific studies demonstrate that timber species breeding programs, when correctly planned and implemented, do not lead to a narrowing of genetic diversity. On the contrary, modern forestry breeding methodology encompasses the genetic variability within a given area, transmitting it through improved seeds and clones into artificial orchards during forest regeneration, thereby contributing to the preservation of the best gene pool. Most scientists emphasise the potential of assimilating clone archives of plus trees and trial crops in forestry. Researchers argue that they all contain valuable genetic material – *ex situ* – which is the basis for the conservation of genetic diversity.

## Conclusions

The conclusions drawn from the research convincingly demonstrate that the state of the gene pool in Kyrgyzstan's forest ecosystems is shaped by the optimisation of the selection policy in the industry. The breeding modernisation of Kyrgyzstan's forestry should focus on the gradual replacement of extensive forest management methods with intensive ones based on the principles of sustainable development. Priorities for the sustainable development of forest ecosystems include sound strategic planning for the innovative and technological development of the forestry industry, as well as a system of effective regeneration and preventive measures. The preservation of genetic variability is, in this case, a necessary condition for adaptation to the dynamics of exogenous conditions and successful selection.

In Kyrgyzstan, it is deemed appropriate to apply the successful practical experience of other countries, which will provide the basis for addressing the current issues of identifying reserves for preserving genetic diversity. The practical experience of Sweden in the context of seven alternative forest timber breeding programmes could be partially applied in the Kyrgyz context. Analysis of the impact of modern tree breeding activities on the dynamics of genetic diversity shows that FSOs are the optimal source of improved seeds for forest regeneration. The study paid particular attention to the potential of background pollination in FSOs, considering the dual concept of both reducing the selection effect and simultaneously increasing the level of genetic variability in the progeny. At the same time, it was established that clonal selection – the foundation of clonal forestry – contributes to a narrowing of genetic diversity. If modern scientific recommendations are followed, the reduction of genetic diversity can be minimised. The use of the family forest management concept, which is based on vegetative propagation, significantly intensifies the level of genetic variability in the progeny. An approach based on the selection of multiple populations creates optimal preconditions for combining intensive long-term selection and maximum preservation of the gene pool of timber species.

The development and integration of innovative monitoring and forecasting systems as a primary resource for intensifying the effectiveness of breeding technologies in forestry is a priority area for future research. Of particular importance is the integration of successful international experience, and the development and implementation of innovative breeding methods based on the principles of sustainable development.

## Acknowledgements

None.

## Conflict of Interest

None.

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# Сучасні методи селекції в лісівництві, спрямовані на збереження генетичної різноманітності

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**Анотація**. Дослідження присвячено аналізу впливу сучасних селекційних заходів у лісівництві на рівень генетичної різноманітності лісових деревних порід. Виявлено, що основним джерелом поліпшеного насіннєвого матеріалу для генетичного відтворення лісів є базові лісонасіннєві плантації. Детально проаналізовано аспекти впливу на показники генетичної варіативності нащадків визначальних чинників – фонового запилення та числа клонів. Вивчено потенціал фонового запилення на лісонасіннєвих плантаціях у контексті суттєвого зниження ефективності селекційних заходів та паралельного підвищення рівня генетичної варіативності потомства. Проведено аналітику даних мінімальної кількості клонів на лісонасіннєвих плантаціях на підставі практичного досвіду розвинених інших країн. Досліджено динаміку варіативності клонів в аспекті фертильності. Визначено можливість впливу клонового добору на генетичну різноманітність деревних порід у напрямку зменшення. Підтверджено, що інтеграція концепції сімейного лісівництва, яка передбачає використання технологій вегетативного розмноження, у селекційну стратегію значно збільшує рівень генетичної варіативності нащадків. Доведено, що система селекції множинних популяцій є основою забезпечення оптимальних попередніх умов для синергізації процесу довготривалої інтенсивної селекції та збереження генофонду деревних порід. Визначено відсутність негативного впливу на генетичну різноманітність реалізації комплексу оптимально спланованих селекційних програм. Водночас, встановлено потенціал інтенсифікації якості збереження генофонду в процесі відтворення лісових екосистем за допомогою поліпшеного насіннєвого матеріалу та клонів у штучних насадженнях. Особливу увагу приділено утриманню *ex situ* – цінного генетичного матеріалу в об'єктах лісового насінництва, в тому числі, лісонасіннєвих плантаціях, випробувальних культурах, архівах клонів плюсових дерев. У процесі дослідження доведено, що імплементація сучасних інноваційних рішень і наукових рекомендацій дає змогу звести до мінімуму процеси зменшення генетичного різноманіття лісових порід. Результати можуть знайти практичне застосування в сучасних селекційних програмах у лісівництві

**Ключові слова**: клонова технологія; соматичний ембріогенез; фонове запилення; *ex situ*; кількість клонів

Received: 15.04.2024; Revised: 19.07.2024; Accepted: 15.08.2024

UKRAINIAN JOURNAL OF FOREST AND WOOD SCIENCE

Journal homepage: https://forestscience.com.ua/en
*Ukrainian Journal of Forest and Wood Science*, 15(3)

UDC 630*228.2:633.872.1
DOI: 10.31548/forest/3.2024.116

# State and ameliorative properties of old original oak stands

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**Abstract**. The ameliorative properties of forest stands are essential for developing effective measures for environmental protection and sustainable use of forest resources. The purpose of the study was to assess the current condition and performance of erosion control properties of old

***Suggested Citation:***
Maliuha, V., Minder, V., Khryk, V., Sytnyk, O., & Levandovska, S. (2024). State and ameliorative properties of old original oak stands. *Ukrainian Journal of Forest and Wood Science*, 15(3), 116-133. doi: 10.31548/forest/3.2024.116

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oak stands of natural origin. The method of assessing the condition of old oak plantations using an integral indicator that takes into account biometric, ameliorative and health characteristics of stands, as well as agrochemical indicators of the soil has been tested. Field work was carried out on four experimental plots, where 794 age-old trees were enumerated. Comprehensive studies included determination of biometric indicators, analysis of root systems, detection of the content of available forms of nitrogen, mobile phosphorus, mobile potassium in soil. Soil hardness was measured with a durometer and soil water permeability using steel cylinders. High values of integral indicators were obtained in the experimental areas, which range from 11.9 to 19.7%. They guarantee the effective performance of erosion control properties by native old-growth forests. It has been researched that the proposed integral indicator of forest stand condition not only allows for assessing their current state but also demonstrates the effective control of erosion and ecological functions of the stand. It was established that essential requirement is to convert the absolute values of various indicators into relative values, with mandatory consideration of their positive or negative impacts on the forest stands themselves. It was found that an integral condition indicator can be used for erosion control plantations of any age range. The results can be used to develop biodiversity conservation programs and establish effective strategies for managing forest resources

**Keywords**: index of the integral condition of the stand; water permeability; hardness; erosion control properties; biometric indicators

## Introduction

Forests play a crucial role in preserving biodiversity, which forms the basis of ecological stability in forest ecosystems. They provide a unique habitat for numerous plant and animal species, including rare and endangered ones. Studying the ameliorative properties of forests allows for the development of effective management and utilization strategies aimed at preserving their natural potential and improving the quality of forest environments. This approach helps achieve a balance among ecological, social, and economic aspects of forestry, crucial for sustainable development and ensuring future generations' access to natural resources.

The relevance of the scientific research topic stems from the necessity to assess the comprehensive indicator of the condition of naturally occurring ancient oak forests. This evaluation is crucial for understanding ecosystem health, biodiversity conservation, and sustainable forest management practices.

Old original oak stands are critically important for maintaining biodiversity as they provide habitats for numerous species of plants, animals, and microorganisms. Oak forests play a significant role in reducing carbon emissions, which is a key factor in combating climate change. According to G. Piovesan *et al*. (2022) they also hold economic value due to their high-quality timber and cultural significance as part of natural heritage, underscoring the need for their conservation and study.

Old forests are important ecosystems because they have both root systems and canopy, which makes it possible to fix a large amount of atmospheric $CO_2$, produce oxygen, and create a unique microclimate and living conditions, unlike young and monocultured forests. Intensive logging is causing rapid adverse impacts on ecosystems and climate. Mature forests persist in absorbing carbon and fixing nitrogen. Old trees control the underground conditions necessary for tree regeneration, old-growth forests create a microclimate that slows down global warming and is an essential habitat for many endangered species. P. Chmielarz *et al*. (2023) researched old trees produce phytochemicals with many biomedical properties. They note that existing old trees are very important for biodiversity, as they also preserve elements of cultural heritage before industrial times.

In many ecosystems worldwide, large old trees are found as isolated individuals or small, scattered groups, qualifying them as small natural features. Despite their spatial limitations, these solitary or small groups of old trees play vital ecological roles, such as carbon storage and providing wildlife habitats. Protecting and managing these large old trees as small natural features is crucial for preserving these roles and often necessitates targeted, small-scale conservation strategies. These strategies may include prohibiting the felling of trees above a certain size, installing microfences to prevent grazing threats, and creating buffer zones of other vegetation to shield them from fire and chemical exposure. Studies on the growth and condition of ancient oaks are actively ongoing. According C. Cannon *et al.* (2022), ancient trees are unique forest assets that take centuries to develop. These old-growth trees significantly influence generation time and population fitness, transcending centennial ecological cycles. Consequently, they are crucial for the forest's long-term ability to adapt to changing climate conditions and provide invaluable data on ecological history and individual longevity. Given that they cannot be replaced by reconstruction or regeneration for many centuries, their protection is essential to preserving their irreplaceable diversity.

In scientific research of J. Zawadka (2020) it was noted environmental factors affecting the condition and growth of old oaks and other trees are of exceptional importance; trends in growth and age of common oak along the amplitude gradient; hundred-year climate changes, as well as the impact of negative biotic, biotic and anthropogenic factors on old oak plantations; structural diversity of oak plantations in the green zone of forest parks and the protection of tree natural monuments in European countries. Most often, appraisers focus on biometric assessment studies, foresters on forestry, land amelioration on agroforestry, and soil scientists on obtaining indicators that characterize soil properties. It is not easy to combine various indicators, especially when they have different dimensions (Fawzy *et al.*, 2020).

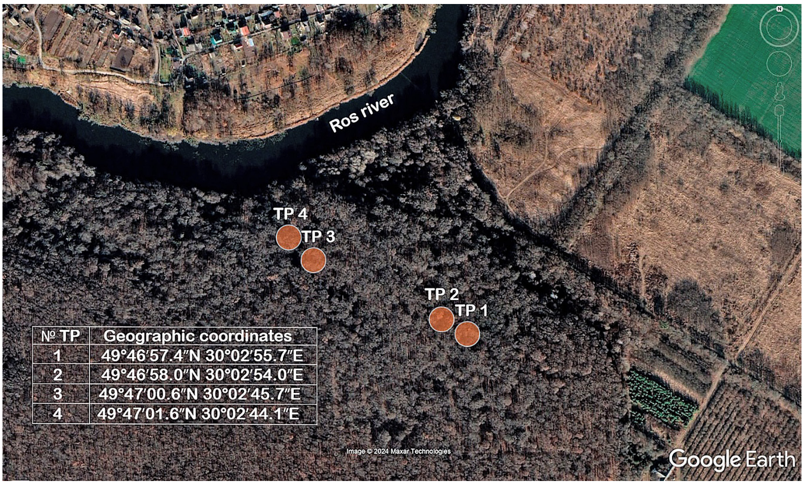
During the study of the state and improvement of eroded soils V. Maliuha *et al*. (2021) tested the coefficient of soil improvement as an average integral indicator that takes into account individual elements of soil properties. According to a similar methodological approach, it was proposed to use an integral indicator of the condition of forest plantations, taking into account biometric, ameliorative, health features of forest plantations and soil properties. To obtain an integral indicator of the condition of forest plantations, calculations are performed in advance, which ensure the reduction of all various indicators with their absolute values to relative values in comparison with the selected control.

The purpose of the study was to comprehensively assess the current condition and performance of erosion control properties of old-age oak stands of natural origin.

## Materials and Methods

Comprehensive studies of age-old oak stand of natural origin were carried out on the territory of the "Koshyk" tract of the Educational and Experimental Forestry of the Bila Tserkva

National Agrarian University. The area of the massif was 7.5 hectares, on which 4 trial plots (TP) were selected (Fig. 1). Field research was conducted during September-December 2022. The study of old oak plantations of natural origin, the LIDAR surveying was used, which allows you to quickly obtain detailed and spatial information about the short-term dynamics of "windows" in the canopy of old oak plantations. This technology offers a valuable means of studying patterns of forest loss and understanding the dynamics of forest ecosystems at a narrower scale than previously possible using traditional methods (Vepakomma *et al.*, 2008).



| № TP | Geographic coordinates |
|---|---|
| 1 | 49°46′57.4″N 30°02′55.7″E |
| 2 | 49°46′58.0″N 30°02′54.0″E |
| 3 | 49°47′00.6″N 30°02′45.7″E |
| 4 | 49°47′01.6″N 30°02′44.1″E |

**Figure 1.** Location of trial plots on the territory of the "Koshyk" tract

**Source:** Google Earth

Based on the method of applying an integral indicator, which takes into account biometric, amelioration and health characteristics of stands, as well as agrochemical indicators of the soil. The following indicators were considered in the study: biometrics – height of trees, m; diameter, cm; stock, $m^3$/ha; the basal area – $m^2$/ha, etc.; amelioration – root surface area, $cm^2$; soil hardness, kg/$cm^2$; soil compaction density, g/$cm^3$ and its water permeability, mm/min; forestry, characterizing health condition – the number of affected trees, pcs. and health condition index; agrochemistry – the content of available forms of nitrogen, mobile phosphorus, mobile potassium, mg/kg, humus, %, etc. (Khryk, 2024).

All trees were numbered in all trial plots, and a list of trees by diameter was made (Fig. 2a). At each trial plot, the heights of 12-15 trees were measured with an altimeter-eclinometer RM-5 (Finland), followed by construction of graphs of height curves. One model tree was selected based on the average height and diameter within each trial plot. Next to each model tree, at a distance of 3 m, samples of the root-containing layer of the soil were taken using a soil sampler (Fig. 2b). Test samples of soil cores were taken in mutually perpendicular directions from the middle tree of an old oak tree at depths of 0-10, 10-20, 20-30, 30-40, and 40-50 cm (Fig. 2b). A total of 67 samples were selected.

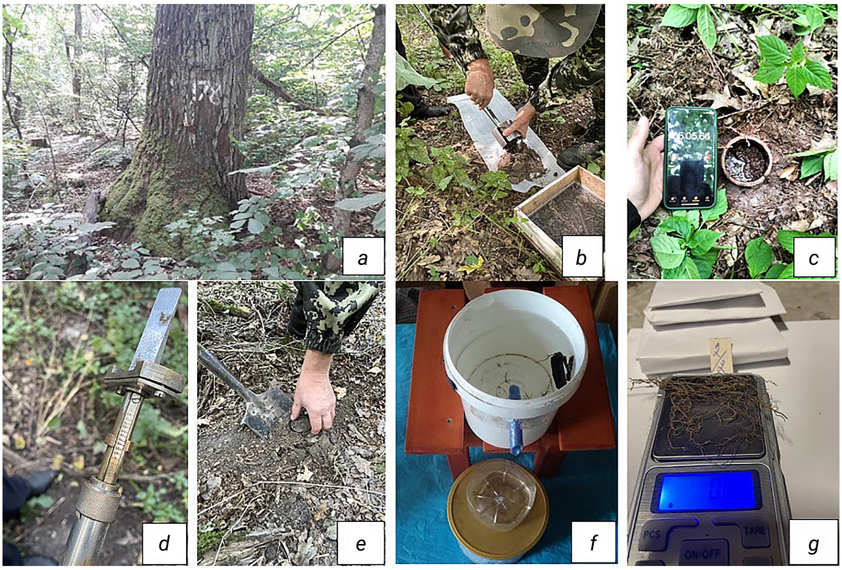


**Figure 2.** Field and chamber work

**Note:** a) numbered age-old oak on the trial plot; b) sampling of soil cores using a drill; c) measurement of water absorption time by the soil; d) hardness tester; e) use of a cutting ring to determine the density of the soil composition; f) determination of the volume of conductive roots by the xylometric method; g) measurement of the weight of active roots

**Source:** developed by the authors

In parallel, the roots of the common oak were selected from the obtained cores and divided into fractions: physiologically active roots (with a diameter of < 2 mm) and conducting roots (with a diameter of > 2 mm). Their volume was determined by the xylometric method by measuring the displaced water during immersion of the roots in a wet state in water (Fig. 2f). The mass of raw and dry roots was determined using electronic scales with an accuracy of 0.01 g (Fig. 2g). Root diameters were determined using a micrometer, which made it possible to establish the average value of the index of each fraction. For each fraction, the surface areas of the root samples were calculated according to formula (1):

$$S = 4 \cdot \frac{V}{D}, \tag{1}$$

where, $S$ is the lateral surface of the roots, cm$^2$; $V$ – root volume of this fraction, cm$^3$; $D$–the average diameter of the fraction, cm. Using a soil sampling device with a diameter of 10 cm, soil cores were taken from experimental plots in 5-fold repetition to obtain mixed soil samples from each 10-cm layer to a depth of 50 cm of the active root-containing horizon. Mixed soil samples for laboratory analyses weighing 1 kg were formed (Pawlik *et al.*, 2023). Soil hardness was measured by I. Golubev's hardness tester in 20 repetitions with subsequent statistical data processing (Fig. 2d). A total of 80 soil hardness measurements were made.

The time of water absorption by the soil was measured using steel cylinders with a diameter of 80 mm and a height of 100 mm by burying the cylinder halfway into the soil and filling the upper part (50 mm) with water. The stopwatch determined the absorption time of a 50 mm layer of water, which corresponds to torrential rainfall. The number of measurements is

10 times. A total of 40 measurements of water permeability of the soil were made.

Water permeability is calculated by the ratio of the amount of absorbed water to the time of its absorption (Fig. 2c). The compaction density of the soil was determined using a cutting ring with a diameter of 50 mm and a height of 30 mm. The selection of soil samples was carried out both from the surface and from depths of 10-50 cm using a soil sampler. The soil from the cutting ring was transferred to an aluminum box for drying in a cabinet to constant weight. The assembly density (volumetric mass) was determined by dividing the weight of dry soil by the volume of the cutting ring (Fig. 2e). The content of nutrients was obtained by laboratory tests of soil samples in the certified laboratory of the Bila Tserkva National Agrarian University. Nutrient stocks of available forms of nitrogen ($N-NO_3+N-NH_4$), mobile phosphorus ($P_2O_5$), mobile potassium ($K_2O$) were determined. The stock is calculated by the product of their content (mg/kg) by the density of the assembly and by the thickness of the soil layer of 50 cm. Researchers V. Khryk *et al*. (2024) developed a scale for assessing the state of forest stands (Table 1), which was used to determine the integral condition of the studied stands.

**Table 1.** Scale for assessing the condition of forest stands

| Serial number | Integral indicator | Value, % | Stand condition |
|---|---|---|---|
| 1 | very high | 0-20 | safe |
| 2 | high | 21-40 | attenuated |
| 3 | average | 41-60 | weak |
| 4 | low | 61-80 | very weak |
| 5 | critical | 81-100 | threatening |

**Source:** developed by the authors based on V. Khryk *et al*. (2024)

The experimental studies conducted on plants comply with international standards Convention on Biological Diversity (1992). According to a visual inspection of all stands, the stand on TP 4 was determined to have with the weakest health conditions (Resolution of the Cabinet of Ministers of Ukraine No. 756, 2016) and adopted by the authors of this study and was accepted as the basic (control) – for a comparative assessment of the integral condition of the investigated age-old stands on trial plots 1-3.

## Results and Discussion

The concept of plantation condition has many aspects. Plantations are constantly in flux: on the one hand, their condition depends on forest conditions, and on the other hand, they are capable of creating new conditions that will be most favourable for growth and development. The condition of forest plantations can be assessed from different positions. With the help of sylvicultural and biometric indicators, it is possible to assess the condition of plantations, taking into account their qualitative (class of rating) and quantitative (stand stock) productivity. There are indicators that allow establishing the health condition of plantations. For example, a tree stand has achieved high productivity, but under certain conditions has lost its biological stability due to the manifestation of the action of forest pests or pathogens. For this, there is already an indicator of the health condition index (Resolution of..., 2016).

The condition of manifestation of ameliorative properties of old oak stands was determined by a number of soil characteristics, including compaction density, hardness, water permeability, etc. Forests have numerous ecological functions: energy, water regulation, water absorption, soil protection, siltation, soil creation, restoration, recreation, sanitary and hygienic, aesthetic, climate regulation, ecological stabilization, etc. Their effective ability to perform many functions is closely related to the condition of the plantations.

Forestry and biometric characteristics of age-old oak forest plantations of natural origin are presented in Table 2. They are pure in composition, aged from 200 to 214 years. Trial plot 1 is distinguished by the average diameter, the rest do not have a reliably significant difference. The average heights are within the II class of rating, which characterizes it as a fairly high quality indicator of the productivity of old stands.

**Table 2.** Forestry and biometric characteristics of stands according to the data of trial plots

| **TP number** | **Stand composition** | **Age, years** | **Number of trees, pcs.** | | **Average** | | **Plot area, ha** | **Class of rating** | **Stock, m$^3$/ha** | **Total stock, m$^3$** |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | **per plot** | **per/ha** | **Diameter,cm** | **Height, m** | | | | |
| 1 | 10Qr | 214 | 321 | 107 | 67.8 ± 0.75 | 29.3 ± 3.1 | 3.0 | II | 510 | 1530 |
| 2 | 10Qr | 204 | 236 | 107 | 64.7 ± 0.75 | 29.1 ± 2.6 | 2.2 | II | 465 | 1023 |
| 3 | 10Qr | 200 | 135 | 104 | 63.5 ± 1.06 | 28.9 ± 3.0 | 1.3 | II | 451 | 586 |
| 4 | 10Qr | 204 | 102 | 102 | 64.6 ± 1.41 | 29.2 ± 2.5 | 1.0 | II | 429 | 429 |

**Note:** Qr – common oak (*Quercus robur* L.)
**Source:** developed by the authors

The area of the trial plots is from 1.0 to 3.0 ha, respectively, and the number of trees is from 102 to 321 pcs., although if you bring the data to an area of 1 ha, the difference in the number of trees on the plots turns out to be insignificant from 107 to 102 trees. Quantitative productivity, which is represented by the stock of trunk wood, is in the range from 429 to 510 m$^3$/ha, which, taking into account the different area of trial plots, provides a total stock of wood from 429 to 1530 m$^3$. From the considered forest biometric indicators, for further comparison of the obtained data, it is advisable to take into account the diameter and stock of plantations, since the rest of the indicators do not have a significant difference.

The following indicators were chosen to evaluate the erosion control properties of the stands: hardness, water permeability of the soil and the study of root systems. It is the selected indicators that most accurately characterize the indicated properties, which depend on the possibility of transferring surface runoff to ground runoff, in order to avoid the possible manifestation of erosion processes as much as possible. With low soil hardness, sufficient water permeability and the spread of root systems, maximum absorption of water by the soil can be ensured, that is, surface (often destructive) runoff can be transferred to safe internal soil runoff. Statistics for determination of soil hardness and assessment of the significance of the difference between the average values of indicators are presented in the Table 3 and 4. The maximum hardness of the soil detected during the control TP 4 is 15.2 kg/cm$^2$. The rest of the obtained hardness indicators on TP 1-3 do not have significant differences.

**Table 3.** Soil hardness statistics

| TP number | Statistics | | | | | |
|---|---|---|---|---|---|---|
| | **N** | **M** | **m** | **σ** | **υ** | **p** |
| 1 | 20 | 9.9 | 0.567 | 2.53 | 25.57 | 5.72 |
| 2 | 20 | 11.8 | 0.663 | 2.97 | 25.14 | 5.62 |
| 3 | 20 | 10.6 | 0.266 | 1.19 | 11.29 | 2.52 |
| 4 (Control) | 20 | 15.2 | 0.571 | 2.55 | 16.74 | 3.74 |

**Note:** N – the number of measurements; M – the average value; m – the error of the average value; σ – mean square deviation; υ – coefficient of variation; p – accuracy of research

**Source:** developed by the authors

**Table 4.** Evaluation of the significance of the difference between the average values of soil hardness indicators

| The difference between the average values on the trial plots | Number of degrees of freedom | Student's criterion $t_{0.05}$ | The difference between the average values on the trial plots | Number of degrees of freedom | Student's criterion $t_{0.05}$ |
|---|---|---|---|---|---|
| 1-2 | 36 | 2.18 | 2-3 | 36 | 1.68 |
| 1-3 | 36 | 1.12 | 2-4 (C)* | 36 | 3.88 |
| 1-4 (C)* | 36 | 6.60 | 3-4 (C)* | 36 | 7.31 |

**Note:** * – the difference is significant; C – control

**Source:** developed by the authors

Therefore, a significant difference in hardness indicators was obtained for all plots compared to the control. A high soil hardness of more than 30 kg/cm$^2$ not only slows down the absorption of rainwater as much as possible, but also often prevents the development of root systems. An important indicator is the water permeability of the soil, and for its determination, the absorption time of a 50 mm layer of water from steel cylinders, which corresponds to the level of an atmospheric downpour, was initially taken into account. The statistics of the absorption time of 50 mm of water are given in the Table 5.

**Table 5.** Statistics of indicators of absorption time of 50 mm of water

| TP number | Statistics | | | | | |
|---|---|---|---|---|---|---|
| | **N** | **M** | **m** | **σ** | **υ** | **p** |
| 1 | 10 | 2.94 | 0.575 | 1.82 | 61.78 | 19.54 |
| 2 | 10 | 6.58 | 1.234 | 3.90 | 59.32 | 18.76 |
| 3 | 10 | 5.50 | 0.629 | 1.99 | 36.19 | 11.44 |
| 4 (C) | 10 | 10.10 | 0.706 | 2.23 | 22.13 | 6.99 |

**Note:** N – the number of measurements; M – the average value; m – the error of the average value; σ – mean square deviation; υ – coefficient of variation; p – accuracy of research

**Source:** developed by the authors

The obtained results of statistical processing of field research data show that the absorption time of a 50 mm layer of water ranges from 2.94 to 10.10 minutes (TP 1-4). At the same time, no significant difference was found between the indicated indicators at TP 2 and 3. An estimate of the significance of the difference between the average values of the absorption time of a 50 mm layer of water is given in the Table 6. A significant difference in water absorption indicators was obtained between TP 1 and TP 2 and 3, as well as compared to the control. Indicators of soil hardness and the time taken to absorb a 50 mm layer of water revealed a direct relationship. A higher hardness index of 15.2 kg/cm$^2$ corresponds to a longer time for absorbing water from a steel cylinder – 10.1 minutes.

**Table 6.** Evaluation of the significance of the difference between the average values of the indicators of the time of absorption of 50 mm of water

| The difference between the average values on the trial plots | Number of degrees of freedom | Student's criterion $t_{0.05}$ | The difference between the average values on the trial plots | Number of degrees of freedom | Student's criterion $t_{0.05}$ |
|---|---|---|---|---|---|
| 1-2* | 16 | 2.67 | 2-3 | 16 | 0.78 |
| 1-3* | 16 | 3.00 | 2-4 (C)* | 16 | 2.48 |
| 1-4 (C)* | 16 | 7.87 | 3-4 (C)* | 16 | 4.87 |

**Note:** * – the difference is significant; C – control

**Source:** developed by the authors

In terms of erosion control, it is important to take into account the peculiarities of the development of root systems, which, in addition to keeping plants in the soil, supplying them with nutrients and water, contribute to the formation of water-resistant aggregate structures and reliably counteract the manifestation of erosion processes (washing and erosion) of the soil, Table 7.

**Table 7.** Ratio of roots in monoliths 50 cm deep

| TP number | Mass of dry roots, g | | | Volume of displaced water, ml | | |
|---|---|---|---|---|---|---|
| | conductive | active | ratio | conductive | active | ratio |
| 1 | 10.48 | 0.80 | 13.1 : 1 | 25.4 | 1.3 | 19.5 : 1 |
| 2 | 8.20 | 0.70 | 11.7 : 1 | 10.5 | 0.8 | 13.1 : 1 |
| 3 | 9.60 | 0.75 | 12.8 : 1 | 17.4 | 1.1 | 15.8 : 1 |
| 4 | 9.39 | 0.89 | 10.6 : 1 | 17.3 | 1.4 | 12.4 : 1 |

**Source:** developed by the authors

The largest mass of roots and, accordingly, the volume of water displaced by it from the xylometer falls on TP 1. It turned out that the ratio of the mass of roots and the volume of displaced water is characteristic of all trial plots in favour of the conductive one, which provides mainly the transport function. At the same time, it contributes to the transfer of surface runoff into the soil due to the spread of roots into deep soil horizons. The most important role of active roots is that, thanks to its own surface area, it ensures direct contact with the soil in supplying plants with water and nutrients from the bulk solution, contributes to the improvement of the soil structure and its water permeability. The surface area of the roots is given in the Table 8.

**Table 8.** Root surface area

| TP number | The average diameter of the roots, cm | | The volume of displaced water, ml | | | Root surface area, $cm^2$ | | |
|---|---|---|---|---|---|---|---|---|
| | conductive | active | conductive | active | total | conductive | active | ratio |
| 1 | 0.73 | 0.03 | 25.4 | 1.3 | 26.7 | 139.2 | 173.3 | 1 : 1.24 |
| 2 | 0.52 | 0.03 | 10.5 | 0.8 | 11.2 | 80.8 | 106.7 | 1 : 1.32 |
| 3 | 0.65 | 0.03 | 17.4 | 1.1 | 18.5 | 107.1 | 146.7 | 1 : 1.37 |
| 4 | 0.67 | 0.03 | 17.3 | 1.4 | 18.9 | 103.3 | 186.7 | 1 : 1.81 |

**Source:** developed by the authors

Despite the fact that the ratio of the mass of the roots and the volume of displaced water was in favour of the conductive one, the ratio between the active and conductive roots in the monoliths was in favour of the active one based on the determined surface area of direct contact with the soil. Therefore, the surface area of active roots was used in further research to assess the condition of plantations by an integral indicator.

In addition to the study of the ameliorative erosion control properties of the plantations, the determination of nutrient stocks in the soil was carried out using the example of the content of agrochemical indicators: available forms of nitrogen, mobile phosphorus and potassium. Taking into account the different absolute values of all experimental indicators, to obtain an integral indicator of the condition of stands, conversions were made to their relative values. For this purpose, TP 4 was chosen as a control. A comparison of stocks of agrochemical indicators that provide plants with food is given in the Table 9.

**Table 9.** Comparison of nutrient stocks in a 50 cm soil layer

| TP number | Available forms of nitrogen ($N\text{-}NO_3$+$N\text{-}NH_4$), mg/kg | | Mobile phosphorus ($P_2O_5$), mg/kg | | Mobile potassium ($K_2O$), mg/kg | |
|---|---|---|---|---|---|---|
| 1 | 613.4 | +11.3% | 3086.7 | +33.0% | 4379.3 | +3.5% |
| 2 | 651.2 | +18.2% | 3475.5 | +49.7% | 3749.4 | -11.3% |
| 3 | 707.9 | +28.5% | 2881.1 | +24.1% | 4350.6 | +2.9% |
| 4 (C) | 551.0 | - | 2321.2 | - | 4229.2 | - |

**Note:** C – control

**Source:** developed by the authors

During the comparison of agrochemical indicators that ensure the supply of nutrients, such as available forms of nitrogen and mobile phosphorus and potassium, a decrease in the indicator of mobile potassium at TP 2 (-11.3%) was established. Indicators of the health state of stands are also taken into account, in particular, the presence of transverse cancer of common oak, the total percentage of affected trees and the index of the health condition of plantations, which is given in Table 10.

**Table 10.** Comparison of indicators by health condition

| TP number | Transverse cancer of common oak, % | | Number of affected trees, % | | Health condition index | |
|---|---|---|---|---|---|---|
| 1 | 33.0 | +5.7 | 46.4 | +17.0 | 1.96 | +24.0% |
| 2 | 38.7 | -10.6 | 44.9 | +19.7 | 1.49 | +42.2% |

*Table 10, Continued*

| TP number | Transverse cancer of common oak, % | | Number of affected trees, % | | Health condition index | |
|---|---|---|---|---|---|---|
| 3 | 25.5 | +27.1 | 48.5 | +13.2 | 2.48 | +3.9% |
| 4 (C) | 35.0 | - | 55.9 | - | 2.58 | - |

**Note:** C – control

**Source:** developed by the authors

During the calculations, the (+) or (-) obtained relative value of the indicator with the state of the plantation must be taken into account. That is, how will the impact of this indicator on the condition of the plantation be manifested – positively or negatively? The peculiarity of the comparison of indicators of the health condition is that negative values are given to those of them that worsen the condition. Thus, during the calculation of the indicator of transverse cancer compared to the control, an increase in the indicator on TP 2 by 10.6%, a decrease on TP 1 by – 5.7% and on TP 3 by – 27.1%, but for the stand this decrease is a positive phenomenon, and growth is negative, so the signs are reversed. The number of affected trees and indices of health condition are lower than the control, but instead of minuses, pluses are given, since the reduction of the indicated indicators according to the calculation turns out to be a positive phenomenon for stands.

Among the ameliorative indicators, the following indicators were selected: surface area of active roots, hardness and water permeability of the soil. In part, the role of active roots has been considered earlier, it is worth noting that it takes the most active part in improving the properties of the soil, both physical (loosening, strengthening of waterproofing capacity, resistance to washing and erosion, etc.), and chemical – it contributes to soil formation due to the processes of mineralization and humification of organic matter. Comparison with the control of ameliorative indicators is given in the Table 11.

**Table 11.** Comparison of ameliorative indicators

| TP number | Surface area of active roots, $cm^2$ | | Soil hardness, $kg/cm^2$ | | Absorption time of 50 mm of water, min. | |
|---|---|---|---|---|---|---|
| 1 | 173.3 | -7.2% | 9.9 | +34.9% | 2.94 | +70.9% |
| 2 | 106.7 | -42.8% | 11.8 | +22.4% | 6.58 | +34.9% |
| 3 | 146.7 | -21.4% | 10.6 | +30.3% | 5.50 | +45.5% |
| 4 (C) | 186.7 | - | 15.2 | - | 10.10 | - |

**Note:** C – control

**Source:** developed by the authors

The comparison of ameliorative indicators also warrants clarification. While the decrease in the surface area of active roots compared to the control is evident, further explanation is needed for the soil hardness and the absorption time of 50 mm of water. A decrease in the value of the soil hardness indicator for plantations is a positive thing. Under such conditions, root systems develop better and atmospheric precipitation is better absorbed by the soil. Absorption time decreased, this is also a positive phenomenon because more moisture is absorbed in a shorter period of time (50:2.94 = 17.0 mm/min, and 50:10.1 = 5.0 mm/min), which corresponds to the water permeability indicator. Absorption time and hardness are directly related, while hardness and water permeability indicators have an inversely proportional relationship. They provide an opportunity for the optimal spread of root systems due to a certain hardness and moisture of the soil, which is related to water permeability. Both indicators affect soil erosion processes. For example, with significant hardness, the development of root systems becomes impossible, which worsens their binding effect and reduces the water-absorbing role to a minimum, and as a result, concentrated surface runoff leads to soil washing and erosion.

Two of the biometric indicators were chosen to obtain an integral condition indicator – the average diameter and the stock (Table 12). A total of 11 indicators were selected during complex studies to establish an integral condition indicator, the comparison of which is shown in the Tables 9-12. The integral indicator of the condition of stands is the average value of the algebraic sum of all relative compared indicators, eleven of which are considered in this study.

Most often, certain aspects of the plantations are studied and analysed, taking into account certain indicators that are obtained using separate methods and have their own absolute values. To assess such multidimensionality as natural forest stands, in particular age, a generalized integrating indicator is needed.

**Table 12.** Comparison of biometric indicators

| TP number | Diameter of an average tree, cm | | Stock of the stand, m$^3$/ha | |
|---|---|---|---|---|
| 1 | 67.8 | +4.9% | 510 | +18.9% |
| 2 | 64.7 | +0.2% | 465 | +8.4% |
| 3 | 63.5 | -1.7% | 451 | +5.1% |
| 4 (C) | 64.6 | - | 429 | - |

**Note:** C – control

**Source:** developed by the authors

As for the biometric characteristics, it is possible to notice a non-significant difference between the indicators of the average diameters of TP 2 and 3 with the control. The diameter of the average tree on TP 2 exceeds the control by 0.2%, and on TP 3 it is smaller by 1.7%, which was discussed earlier during the comparison of statistics. The stock of trees in all areas is higher than the control. The calculation of the integral indicator of the condition of the stands is given in the Table 13.

**Table 13.** Calculation of the integral indicator of the condition the stands

| TP number | N | $P_2O_5$ | $K_2O$ | Toc | Ta | Ihc | S | T | Wa | D | Stock | Iic |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 11.3 | 33.0 | 3.5 | 5.7 | 17.0 | 24.0 | -7.2% | 34.9 | 70.9 | 4.9 | 18.9 | 19.7 |
| 2 | 18.2 | 49.7 | -11.3 | -10.6 | 19.7 | 42.2 | -42.8% | 22.4 | 34.9 | 0.2 | 8.4 | 11.9 |
| 3 | 28.5 | 24.1 | 2.9 | 27.1 | 13.2 | 3.9 | -21.4% | 30.3 | 45.5 | -1.7 | 5.1 | 14.3 |

**Note:** N – available forms of nitrogen; $P_2O_5$ – mobile phosphorus; $K_2O$ – mobile potassium; Toc – transverse oak cancer; Ta – the number of affected trees; Ihc – health condition index; S – surface area of active roots; Hs – soil hardness; Wa – absorption time of 50 mm of water; D – average diameter; Iic – integral indicator of condition

**Source:** compiled by the authors

Therefore, an analysis of eleven indicators was carried out, which made it possible to obtain a synthesizing result of the assessment of the condition of aged oak stands of natural origin. Another approval of the integral indicator of the state of plantations took place. Under the conditions of comparison of the assessed plantations of TP 1, 2, 3 with the control of TP 4, the integral indicators of the conditions were as follows: the result – 19.7% has TP 1, and further in descending order – 14.3% of TP 3 and – 11.9% at TP 2.

The number of indicators can be significant, which makes it possible to take into account their cumulative effect on the final result in more detail. It is especially important to use such a methodical approach to evaluate a large number of objects that will require comparative evaluation.

An old age tree is one that holds biological, cultural, or aesthetic significance due to its notable age, size, or condition. C. Leuschner & H. Ellenberg (2017) proved such trees are of great interest as they serve as living witnesses to the past and relics of former landscapes. These grand old age trees are among the most iconic life forms on Earth and play a crucial role in various terrestrial ecosystems. M. Gilhen-Baker *et al.* (2022) examined those large old trees have an active impact on ecosystem conservation, productivity and climate improvement.

A. Kushnir & I. Vakulyk (2018) described that big old age trees are an important part of shared cultural heritage, providing people with aesthetic, symbolic, religious and historical markers. Bringing their many ecological, oceanic, therapeutic and socio-cultural benefits to the fore and learning to appreciate old trees holistically can contribute to halting the global decline of old growth forests.

D. Lindenmayer & W. Laurance (2017) and D. Lindenmayer (2017) analysed the state of old oak stands during research on the influence of climate on vegetation change in the eastern regions of the USA. Large old trees play an important ecological role in the hydrological regime, nutrient cycling, etc. Age-old plantations affect the spatial and temporal distribution and number of individuals of one species and populations of many other plant and animal species. Researchers A. Larionova & A. Klestch (2019) suggested that important parameters of old-growth trees, such as height, life span, and excessive sparsity, which provide competitive advantages in an undisturbed environment, can make such trees highly vulnerable to a number of anthropogenic impacts.

Centuries-old trees suffer from droughts, fires, pests and pathogens, as well as from logging, land clearing, landscape fragmentation and climate change. P. Zarzyński & A. Grzywacz (2019) researched that addressing the above threats is challenging because they often interact and manifest differently in different ecosystems, requiring targeted responses to specific species or ecosystems. According F. Indresputra *et al.* (2023), new management actions are often needed to protect the existing large old trees and to ensure the recruitment of new cohorts of such trees. In agro-industrial and urban areas, there is a need to conserve and preserve individual specimens of centuries-old trees. Landscape-level approaches will be needed, such as protecting sites where large old trees are most likely to occur. A. Arif *et al*. (2024) noted the trees demonstrate significant potential for land reclamation due to their ability to thrive in high salinity conditions. Their adaptability not only aids in soil stabilization but also improves the overall ecological health of degraded areas.

However, this raises problems related to the likely redistribution of trees depending on climate change, as old trees may exist at this time in places unsuitable for the development of new communities of the same species. Researchers P. Adamič *et al*. (2023) studied suitable future ecological domains for a species may exist in new places where it has never been encountered before. Future distribution and conservation of large old trees may require conflicting responses, including assisted migration via seeds or seedlings to new locations. K. Kimic (2021) studied the global decline in the number of large old trees and their importance to ecosystems, which may be relevant to the assessment of the condition of old-growth oak stands.

According to I. Vakuluk & O. Balalaieva (2018), the effectiveness of such approaches is limited by the ecological characteristics of large old trees (e.g., the presence of hollows) dependent on other species, such as termites, fungi, and bacteria.

Morphological indicators of old trees according to N. Sukri *et al*. (2023) vary greatly on a species-to-species basis, creating significant challenges in identifying large old trees and requiring an ecosystem-specific and identification method that is rarely readily transferable to other species or ecosystems. Such variability is also manifested in the marked interspecific relationships of the main characteristics of old-growth trees, including the root system, crown habit, degree of development of the bark microenvironment, and prevalence of gaps.

Overall, the significant number of indicators allows for a more detailed consideration of their cumulative effect on the final result, which is important when evaluating a large number of objects for comparative analysis. Old trees are not only biologically, culturally, and aesthetically significant, but also play a critical role in various ecosystems by providing hydrological regimes, nutrient cycling, and numerous ecosystem processes. This underscores the need for their protection and adaptation to climate change to maintain ecological stability.

## Conclusions

The analysis and comparison of taxation indicators shows that the leading position is occupied by TP 1, where the stock of stem wood is 510 $m^3$/ha or 18.9% higher than the control. The average diameter is 67.8 cm, which is 4.9% higher than the control. The large difference in stock is caused by the difference in diameters and the number of trees. Analysing the nutrient reserves, found that TP 3 has advantages in terms of available nitrogen forms, which is 28.5% more than the control. In terms of mobile phosphorus reserves, TP 2 has the best position, which is 49.7% higher than the control. There is no big difference in mobile potash reserves, but TP 1 is 3.5%.

The study of the health condition showed the best results in TP 3, where the presence of cross cancer is 27.1% less than in the control. The smallest number of affected trees was found in TP 2 (by 19.7%). The health condition index of 1.49, which is typical for healthy plantations, corresponds to the conditions of TP 2. The analysis of reclamation indicators shows that the best results in terms of the surface area of active roots were obtained in the control. This is due to the presence of the largest amount of undergrowth and undergrowth in this area. In terms of soil hardness, the best result was found in TP 1 – 9.9 kg/$cm^2$, which differs by 34.9% compared to the control. The time of absorption of 50 mm of water layer was also the best in TP 1 (70.9% faster compared to the control).

On the basis of the results of the comprehensive assessment of the condition and performance of the properties of the aged oak stands of natural origin of the Educational Farm of the Bila Tserkva National Agrarian University, it can be concluded that very high values of integral indicators, which do not exceed 20%, have been obtained. They guarantee a general safe condition in the performance of erosion control properties by studied forest stands. Under the conditions of comparison of the assessed plantations of TP 1, 2, 3 with the control of TP 4, the integral indicators of the conditions were as follows: the result – 19.7% has TP 1, and further in descending order – 14.3% of TP 3 and – 11.9% at TP 2.

Therefore, the proposed integral indicator of the condition of plantations provides the possibility of applying a comprehensive approach to their assessment, taking into account the manifestation of various ecological properties by forest stands. It is crucial to convert various indicators from absolute values to relative values, taking into account whether they have positive or negative effects on the forest stands. The methodology for assessing the integral indicator of plantation condition requires comprehensive testing. The need for the most complete assessment of the condition of plantations as a multifaceted research object remains, which indicates its relevance. Its refinement and revision may not be ruled out, but this will be proved by further testing.

## Acknowledgements

None.

## Conflict of Interest

None.

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**Анотація**. Меліоративні властивості лісових насаджень мають важливе значення для розробки ефективних заходів з охорони довкілля та сталого використання лісових ресурсів. Вивчення цих лісів допомагає розробити ефективні стратегії їх збереження та сталого використання. Актуальність теми дослідження визначається необхідністю апробації методики оцінки стану вікових дубових насаджень за допомогою інтегрального показника. Метою дослідження було оцінити сучасний стан та ефективність протиерозійних властивостей старих дубових насаджень природного походження. Апробовано методику оцінки стану вікових насаджень дуба за інтегральним показником, що враховує біометричні, меліоративні та санітарні характеристики насаджень, а також агрохімічні показники ґрунту. Польові роботи проводились на чотирьох дослідних ділянках, де обліковано 794 вікові дерева. Комплексні дослідження включали визначення біометричних показників, аналіз кореневої системи, визначення вмісту в ґрунті доступних форм азоту, рухомого фосфору, рухомого калію. Твердість ґрунту вимірювали за допомогою твердоміра, а водопроникність ґрунту – за допомогою сталевих циліндрів. На дослідних ділянках отримано високі значення інтегральних показників, які коливаються від 11,9 до 19,7 %. Вони гарантують ефективні протиерозійні властивості місцевих старовікових лісів. Досліджено, що запропонований інтегральний показник стану деревостанів не тільки дозволяє оцінити їх поточний стан, але й демонструє ефективний контроль ерозійних та екологічних функцій деревостану. Встановлено, що важливою вимогою є переведення абсолютних значень різних показників у відносні, з обов'язковим врахуванням їх позитивного чи негативного впливу на самі лісові насадження. Встановлено, що інтегральний показник стану може бути використаний для протиерозійних насаджень будь-якого вікового діапазону. Результати можуть бути використані для розробки програм збереження біорізноманіття та створення ефективних стратегій управління лісовими ресурсами

**Ключові слова**: індекс інтегрального стану деревостану; водопроникність; твердість; протиерозійні властивості; біометричні показники

Received: 29.04.2024; Revised: 30.07.2024; Accepted: 15.08.2024

UKRAINIAN JOURNAL OF FOREST AND WOOD SCIENCE

UKRAINIAN JOURNAL OF FOREST AND WOOD SCIENCE

Journal homepage: https://forestscience.com.ua/en
*Ukrainian Journal of Forest and Wood Science*, 15(3)

UDC 674.02:674.038.5
DOI: 10.31548/forest/3.2024.134

# Gluing of thermally modified silver fir wood planed by horizontal milling machine

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**Abstract**. This study was conducted to provide information regarding the quality of gluing of Silver fir wood (*Abies alba* Mill.) planed at different feed speeds after thermal modification. Four groups of sixteen air-dried fir samples were prepared. Three groups were thermally modified at different temperatures (160°C, 190°C, and 220°C) for 3 hours. The processes that followed included planning with two feed speeds (half of the samples at 3m/min and the other half at 10 m/min), the gluing, and finally, conducting mechanical tests to assess shear strength and wood failure. The gluing shear strength underwent a progressive decrease with increasing modification temperature for both feed speeds, with reductions ranging from 1.37% to 14.63% compared to natural wood.

***Suggested Citation:***
Ajdinaj, D., Bekteshi, L., Ahmeti, A., & Mine, L. (2024). Gluing of thermally modified silver fir wood planed by horizontal milling machine. *Ukrainian Journal of Forest and Wood Science*, 15(3), 134-147. doi: 10.31548/forest/3.2024.134.

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Wood failure did not show a linear relationship, with a decrease at 160°C but an increase at higher temperatures compared to natural wood. The feed speed had a significant effect on gluing shear strength, with higher feed speed resulting in decreased strength for natural wood but increased strength for thermally modified wood. Thermal modification of fir wood at temperatures of 220°C had a detrimental effect on the gluing shear strength and wood failure. This was caused by the deterioration of wood components and alterations in mechanical properties. The results of this study offer significant knowledge for improving the gluing process and establishing appropriate parameters for thermally modified fir wood. This type of wood has potential uses in the wood sector, specifically in the manufacturing of engineered wood products

**Keywords**: fir wood; thermal modification; gluing; shear strength; wood failure

## Introduction

Wood is the most environmentally friendly construction material available. However, it also has certain drawbacks. The material exhibits a high degree of anisotropy. The characteristics of this substance exhibit significant variation and it is highly susceptible to damage from exposure to moisture.

In order to mitigate certain drawbacks, wood has undergone various modifications and treatments. According to a study by S. Cao *et al.* (2022), thermal modification of wood is the most commercially advanced among all the many wood modification technologies that have been researched. Wood undergoes controlled heating in this technique, which enhances its dimensional stability and biological endurance. There is consistently a decrease in mechanical characteristics. A good approach of thermally modified wood (TMW) to gluing would significantly expand its use. In this framework many influencing factors related to technological parameters applied during thermal modification, to wood properties and its surface preparation, to adhesive and to technological parameters applied during gluing process, as well as conditions of product service, need to be considered.

In their study, A. Masoumi *et al.* (2023) conducted a comparison to assess the impact of thermal alteration on the adhesive bonding capabilities of yellow poplar wood. The findings indicated that thermal modification led to a decrease in penetration by 31.2% in polyurethane (PUR) and 29% in polyvinyl acetate (PVA). This resulted in a thicker adhesive line, with an increase of 70% in PUR and 2% in PVA. In addition, the PUR glue exhibited a greater shear strength than PVA adhesive, with an increase of 2.7% in non-modified wood and 14% in thermally affected wood. In their study, H.R. Taghiyari *et al.* (2020) examined the shear strength of heat-treated solid wood from three species (beech, poplar, and fir) that were bonded using PVA adhesive supplemented with nanowollastonite (NW). The findings demonstrated that subjecting the specimens to heat treatment led to a substantial reduction in the shear strength of the bonded materials.

Z. Wu *et al.* (2021) and Q. Yu *et al.* (2023) conducted a study on the interfacial alterations of *Pinus massoniana* wood after heat treatment. The aim was to enhance the bonding and coating processes of heat-treated wood. The wood was modified using steam as the medium, at temperatures ranging from 160 to 220°C. According to the findings, hemicelluloses experienced the initial deterioration at a temperature of 160°C, with the highest level of degradation observed at 200°C. Cellulose underwent substantial degradation at a temperature of 200°C, whereas the degradation of lignin was less noticeable at this temperature. The presence of oxygen-containing functional groups such as hydroxyl and carbonyl decreased progressively with increasing temperature, leading to a more intense coloration and a surface that became less reactive.

Thermal treatment is a method employed to enhance the characteristics of wood. In their study, T. Udtaranakron *et al.* (2023) investigated the impact of thermal modification on the mechanical characteristics and adhesive bond strength of rubberwood. The findings demonstrated that elevating the modification temperature had an adverse impact on the mechanical characteristics of rubberwood and led to a reduction in the strength of the wood adhesive bond. In order to enhance the longevity and bonding strength, a composite material consisting of wood and polyvinyl chloride (WPVC) was mixed with thermally modified rubberwood at a temperature of 180°C. This combination yielded the most favourable outcomes in terms of mechanical qualities and the strength of the adhesive bond between the wood components.

In a study conducted by M. Altunok (2021), the researcher examined the adhesive properties of oak and Scotch pine wood samples that had undergone heat treatment. The samples were then bonded using 1K-PUR adhesive under different conditions. The specimens were subjected to various temperature (20°C/35%, 20°C/65%, and 20°C/95%) and relative humidity conditions before being evaluated for adhesion resistance. The findings indicated that both the holding environment and climatic circumstances had a substantial impact on the adhesion resistance. The samples that were stored in A1 conditions and evaluated experienced wood rupture ranging from 70% to 100%. On the other hand, the samples that were tested after being held in A4 and A5 conditions mostly broke apart from the glue joint. The study conducted by A.G. Carvalho *et al.* (2020) assessed the adhesive bonding capabilities of structural adhesives on heat-treated *Mimosa scabrella* and *Pinus oocarpa* wood. The shear strength and percentage of wood failure exhibited variability based on the species, kind of glue, and intensity of heat treatment.

The study by A. Hänsel *et al.* (2023) examines the impact of machining processes on the tensile shear strength of glued lumber, focusing on optimizing face milling tool geometry. The results show that the optimized process, characterized by low surface roughness and minimal microstructure damage, leads to better bonding. F. Rabiei & S. Yaghoubi (2023) optimize the machining parameters for wooden products to minimize surface roughness and process time simultaneously. Using a hybrid technique combining Group Method of Data Handling (GMDH) and the Bees Algorithm (BA), the researchers achieved a 23% improvement in the combined objective function compared to the best experiment. The optimized parameters resulted in a surface roughness of 4.36 $\mu$m and a process time of 93 seconds.

Taking into account the scarce information on the influence of machining conditions regarding to gluing quality of the TMW, the goal of this study was to provide available information related to impact of modification temperature and feed speed on gluing performance of thermally modified Fir wood (*Abies alba* Mill.).

## Materials and Methods

Air dried fir boards of 50×220×2000 mm were used for production of samples. Boards were selected randomly at lumberyard of SINANI (Albania) sawmill. They were produced from logs harvested by sawmill itself from 120 years old forests of central Albania and were transferred to the Faculty of Forestry Sciences of Tirana, where the boards were conditioned for more than 4 months. After conditioning, the mean equilibrium moisture content (EMC) of wood resulted 10.85% (1.093 standard deviation) and the density 0.47 gr/cm$^3$ (0.026 standard deviation), measured respectively according to the standards ISO 13061-1 (2014) and ISO 13061-2 (2014).

64 samples of 25×45×400 mm which presented neither deformations nor wood structure defects were subsequently produced from the sapwood zone. 48 of them were heated applying three different temperatures, 160°C, 190°C and 220°C, at atmospheric pressure for 3 hours (16 samples for each temperature). Heating process was conducted in a temperature controlled small chamber (France Etuves, FRANCE). Before heating, samples were dried at 103 ± 2°C until to the moisture content 0%. The density of oven dried samples resulted 0.46 gr/cm$^3$ (0.019 standard deviation). The increment of temperature from 103°C up to the treatment temperature was set 1 min/°C. The treated samples were cooled and later conditioned until they reached the constant weight. The mean EMC and the mean density of the treated samples at 160°C, 190°C and 220°C resulted respectively 6.77% (1.043 standard deviation) and 0.43 gr/cm$^3$ (0.018 standard deviation).

The control as well as the heat-treated samples were processed along the grain on the section of 45 mm by a planer machine available at the Faculty of Forest Sciences of Tirana (Samco Lab300, Mantovani Macchine, ITALY). Sharp knives were used. The machine had cutterhead diameter 72 mm, rotation speed 5100 rpm and three knives with dimensions 300´30´3 mm. There were applied two feed speeds, 3 m/min and 10 m/min by means of a Type4M feeding system (Olympia, ITALY). 8 samples were processed for each combination temperature-feed speed (8 combinations in total). The cutting depth was 1 mm.

The samples of each group were glued two by two using a one-component PUR glue (Jowat, GERMANY). The samples were assembled according to the standard EN 205 (2016) and to the technical data of the glue manufacturer (Table 1).

**Table 1.** Technical data of the glue according to manufacturer

| Technical parameter | Value |
|---|---|
| Density [g/cm$^3$] | 1.15 |
| Viscosity at 20°C [mPas]<br>(Brookfield, spindle 5, 20 rpm) | 15,500 ± 2,500 |
| Solids content [%]<br>(Jow as test method) | 99 ± 1 |
| Glue spread [g/m$^2$] | 140 ÷ 200[1] |
| Maximum assembly time [min] | 10 |
| Pressure [N/mm$^2$] | 0.6 ÷ 1[2] |
| Minimum pressing time [min] | 10 |

**Note:** 1 –the amount of 150 g/m2 was applied; 2 – the pressure of 1 N/mm2 (1 MPa) was applied
**Source:** compiled by the authors

Cold pressing was applied for 4 hours to achieve the maximal gluing strength, according to the manufacturer's instructions. After conditioning, a total of 448 specimens for shear testing (56 for each combination) were cut from glued samples. Their dimensions were 50×20×20 mm, with the grain direction parallel with the longer edge. The gluing strength was tested by means of a hydraulic testing machine (Controlab, FRANCE), improvising a system referring to the standard EN 205 (2016).

The shear strength for each test was calculated according to equation $T = F_{max}/A$ [N/mm$^2$], where $F_{max}$ was the force of destruction in

Newton and A was the area of tested surface in $mm^2$. The results were submitted to two-factor analysis of variance (ANOVA) to identify significant effect of analysed factors (temperature of modification and feed speed), using IBM SPSS Statistics24 software. Significance was accepted at the $p < 0.05$ level. Duncan test and t-Test were applied to analyse the differences in means.

## Results and Discussion

The thermal modification process involves subjecting the wood to elevated temperatures, typically ranging from 160°C to 240°C, in an oxygen-deficient environment. This treatment enhances certain properties of the wood, such as dimensional stability and resistance to decay, but it can also affect its surface characteristics and chemical composition, potentially altering its gluing properties. In addition to the thermal modification, the surface preparation of the wood plays a crucial role in gluing performance. In this study, we employed a horizontal milling machine for planning the wood surface. The feed speed during this planning process is an important variable, as it affects the surface roughness and, consequently, the wood's ability to form strong bonds with adhesives. Figures 1 and 2 present the gluing shear strength and wood failure values with reference to the modification temperatures and applied feed speeds.

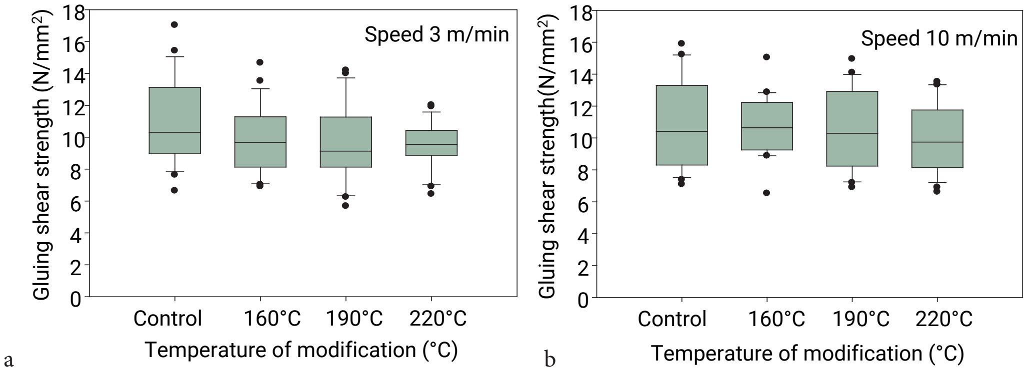

**Figure 1.** The relation between modification temperature and gluing shear strength

**Note:** a – referring to feed speed 3 m/min; b – referring to feed speed 10 m/min

**Source:** compiled by the authors

The gluing shear strength underwent a progressive decrease with reference to that of natural glued wood for all three modification temperatures as well as the two feed speeds. At the lower speed, the control group exhibits a broader range of strengths, while increasing the temperature to 190°C results in a higher median strength and reduced variability, suggesting optimal adhesive performance. At 220°C, although the variability narrows, the strength slightly decreases, indicating diminishing returns at higher temperatures. Comparatively, at the faster speed of 10 m/min, the median strength generally increases across all temperatures, with the most consistent and highest performance observed at 190°C. It suggests that while higher temperatures improve the consistency of adhesive results, the optimal temperature for achieving peak shear strength without compromising consistency appears to be around 190°C, regardless of the application speed.

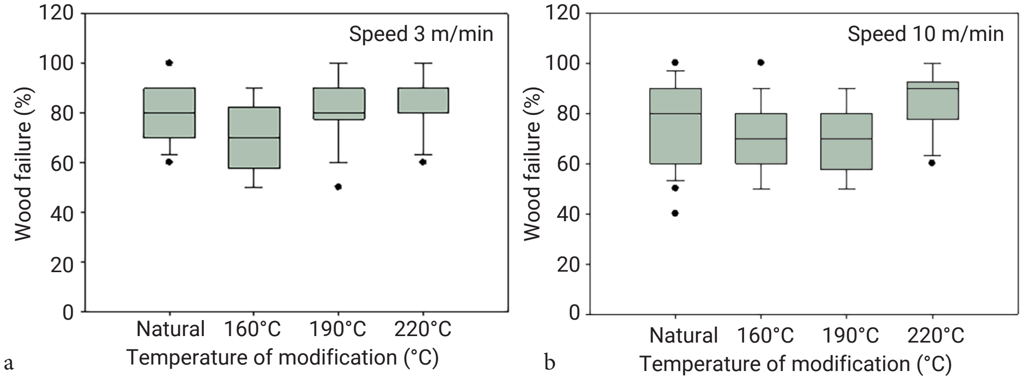

**Figure 2.** The relation between modification temperature and percent wood failure

**Note:** a – referring to feed speed 3 m/min; b – referring to feed speed 10 m/min

**Source:** compiled by the authors

Wood failure did not show a linear relationship like shear strength. For both feed speeds, the failure at the temperature 160°C was lower than that of natural wood, respectively 13.55% for the speed of 3 m/min and 6.55% for the speed of 10 m/min. As for the other temperatures, the failure was bigger than that of natural wood, with the exception of the 190°C temperature for the speed of 10 m/min, where it decreased by 9.52% referring to the failure of natural wood. Regarding the feed speed of 3 m/min, the failure was 1.7% bigger than that of natural wood with reference to the temperature 190°C and 2.83% at the temperature 220°C, whereas for the speed of 10 m/min there was an increase in wood failure, only at the temperature 220°C by11.32%.

Table 2 presents the results of two-factors analysis of variance (ANOVA) of the gluing strength and wood failure for unmodified and thermally modified fir wood at different temperatures, planed with two feeding speeds. The results indicated non-significant effect of the modification temperature for both measured properties, while for the feed speed, a significant effect was noted only for gluing shear strength. The interaction between two analysed factors resulted to be significant at the level 0.05 only for the wood failure.

**Table 2.** Results of the analysis of variance

| Analysed variable | Factor | Sum of squares | df | Mean square | Fisher's F-test | Significance ($p < 0.05$) |
|---|---|---|---|---|---|---|
| Gluing shear strength [N/mm$^2$] | Intercept | 18,182.44 | 1 | 18,182.44 | 1520.317 | 0.000 |
| | Temperature [°C] | 45.796 | 4 | 11,449 | 15,757 | 0.061 |
| | Feed speed [m/min] | 23.624 | 1 | 23,624 | 32,512 | 0.029 |
| | Interaction TF | 1.453 | 2 | 0.727 | 0.141 | 0.869 |
| | Error | 867.982 | 168 | 5,167 | 5,167 | |

*Table 2, Continued*

| Analysed variable | Factor | Sum of squares | df | Mean square | Fisher's F-test | Significance ($p < 0.05$) |
|---|---|---|---|---|---|---|
| Wood failure [%] | Intercept | 1,011,390.584 | 1 | 1011390,584 | 961,445 | 0.000 |
| | Temperature [°C] | 4,162.121 | 4 | 1040,530 | 1,299 | 0.479 |
| | Feed speed [m/min] | 273.485 | 1 | 273,485 | 68,342 | 0.04618 |
| | Interaction TF | 1,601.515 | 2 | 800,758 | 4,197 | 0.017 |
| | Error | 32,054.545 | 168 | 190,801 | | |

**Source:** compiled by the authors

The analysis of variance presented in Table 2 reveals significant statistical influences and interactions between variables on gluing shear strength and wood failure rates. For gluing shear strength, the intercept is highly significant with a Fisher's F-test value of 1520.317 and a p-value of 0.000, indicating a strong baseline effect. Temperature as a factor shows a near-significant influence with an F-test value of 15.757 and a p-value of 0.061, suggesting a potential trend that might become significant with a larger sample size or different temperature settings. Feed speed demonstrates a significant effect on shear strength with an F-test of 32.512 and a p-value of 0.029. However, the interaction between temperature and feed speed (Interaction TF) is not significant ($p = 0.869$). For wood failure, the intercept again shows extreme significance (F-test = 961.445, $p = 0.000$), emphasizing a strong baseline influence. The temperature effect is not significant for wood failure ($p = 0.479$), whereas feed speed and the interaction between temperature and feed speed are significant, with p-values of 0.04618 and 0.017, respectively. These results highlight the critical roles of feed speed and its interaction with temperature in influencing wood failure, suggesting that adjustments in these parameters can substantially impact material performance (Titova & Sobczuk, 2022; Chupa & Zhovtulia, 2023; Sirko *et al.*, 2024).

Table 3 presents the comparative results (Duncan test) of the influence of modification temperature on the gluing shear strength and wood failure. Two homogenous groups were identified emphasizing differences between values referring to control samples, those modified at temperatures 160°C and 190°C and those modified at temperature 220°C. Gluing shear strength and wood failure of unmodified and modified samples at 160°C and 190°C were not significantly different.

**Table 3.** Comparative results for the modification temperature (Duncan test)

| Temperature [°C] | Number of measurements | Gluing shear strength [N/mm²] | Wood failure [%] |
|---|---|---|---|
| Control | 44 | I | A |
| 160 | 44 | I | A |
| 190 | 44 | I | A |
| 220 | 44 | II | B |

**Source:** compiled by the authors

Thus, across all temperatures, 44 measurements were taken, indicating a consistent experimental design. Both the control and 160°C temperatures fall under group I for gluing shear strength and group A for wood failure percentage, suggesting that these conditions did not significantly differ in their effect on the materials. However, at 190°C, the materials still belong to group I for gluing shear strength, showing no substantial increase from lower temperatures, but still maintain group A for wood failure, indicating consistent performance. In contrast, at 220°C, the materials shift to group II for gluing shear strength and group B for wood failure, signifying a notable change in performance which could be interpreted as either a decrease in adhesive effectiveness or a modification in the wood's integrity at this higher temperature. This differentiation highlights the impact of elevated temperatures on material properties and suggests a threshold beyond which the increase in temperature might adversely affect the performance.

The reduction of gluing shear strength converges with the findings of Z. Vidholdová *et al.* (2021), which have had as their object of analysis the gluing of thermally modified conifers with PUR adhesives. Norway spruce wood samples (*Piceaabies* /L./Karst.), thermally treated at atmospheric pressure at temperatures 160°C, 180°C, 200°C and 220°C for 4 hours and glued with one-component PUR adhesive resulted in a gluing shear strength 26%/56% progressively lower, as the modification temperature rose higher.

According to C. Frihart & C. Hunt (2021), gluing shear strength depends on a set of forces acting at the level of contact between the wood substrate and the glue, as well as within the glue and the wood substrate. Its reduction usually occurs either due to the reduction of the adhesion between the glue and the wood, or due to the reduction of the mechanical strength of the wood. The authors agree with the researchers' opinion that the reduction in gluing shear strength of thermally modified wood is usually due to a combination of factors – the decrease in adhesion between the glue and the wood, as well as the reduction in the mechanical strength of the wood substrate. Adhesion is determined by several factors such as surface wettability, surface roughness, adhesive flow, permeability, solidification and wood pH, as noted in J. Iždinský *et al*. (2021) and A. Hänsel *et al*. (2021). Thermal modification of wood has a negative effect on adhesion, because it degrades hemicellulose and as a consequence the number of free hydroxyls in wood decreases. The authors agree with the researchers' opinion that thermal modification negatively impacts adhesion due to the degradation of hemicellulose and the reduction in free hydroxyls in wood, as they observed a decrease in gluing shear strength with increasing modification temperatures.

C. Hill *et al.* (2021) explore the current state of knowledge regarding the hygroscopic and dimensional behaviour of thermally modified timber (TMT) modified under dry (cell wall at nearly zero moisture content) and wet (cell wall contains moisture) conditions. Thermal modification improves the dimensional stability of wood by reducing moisture deformations by 30-90% compared to untreated wood. The anti-swelling efficiency (ASE) of thermally modified beech wood increases with higher temperatures (140-160°C) and longer durations (3 hours), but decreases at extreme conditions (180°C for 5 hours). Dimensional stability reaches its highest value at approximately 20% mass loss during thermal modification, with further improvements only possible in closed systems. The authors' findings partially agree with the conclusions of C. Hill *et al.* (2021) regarding the impacts of thermal modification on wood properties. This suggests that while thermal modification can enhance certain wood properties, it may compromise others, particularly adhesion qualities, which are crucial for practical applications involving glued wood products. At the same time, M. Gaff *et al.* (2023) have shown that the thermal modification process also changes the chemical composition of the wood, particularly the lignin, leading to colour changes and increased thermal stability. Thermowood is an environmentally friendly alternative to tropical wood that is created through a thermal modification process. The process involves heating the wood to temperatures between 160-250°C, which changes the wood's properties and improves its durability, dimensional stability, and resistance to fungi, insects, and weathering. The authors' findings align with M. Gaff *et al.* (2023) on the transformative effects of thermal modification on wood, noting the reduction in mechanical and adhesive qualities at higher temperatures, which underscores the chemical and structural changes.

R. Hasanagić *et al.* (2021) assess the influence of thermal modification on the physical and mechanical characteristics of three distinct wood species – fir (*Abies* sp.), linden (*Tilia* sp.), and beech (*Fagus* sp.). The thermal modification was performed in a controlled laboratory environment using an oven. The modification was carried out at five distinct temperatures (170, 180, 195, 210, 220°C) and with different maximum periods (78, 120, 180, 240, 276 minutes). The findings indicated that the mechanical characteristics of the treated wood exhibited statistically negligible variations at lower temperatures in comparison to the control samples. The authors agree with the findings of R. Hasanagić *et al.* (2021) regarding the negative impact of higher thermal modification temperatures on wood properties, as both studies observe a decline in the strength characteristics with increased temperatures. M. Ninane *et al.* (2021) found that heat treatment of three native European hardwood species – oak, ash, and beech (including steamed beech) – improved their physical and decay resistance properties, making them a promising alternative to tropical woods and chemically treated timber. Specifically, the heat treatment reduced the equilibrium moisture content and increased dimensional stability for all three species. The authors' findings partially align with those of M. Ninane *et al.* (2021) regarding the impact of thermal modification on wood properties. This discrepancy suggests that the effects of heat treatment can vary significantly between different species of wood, potentially due to differences in cellular structure and chemical composition.

According to M.D. Ghalehno *et al.* (2021), heat treatment can have a negative impact on the mechanical properties of Oriental beech wood (*Fagus orientalis*), with higher temperatures and longer durations resulting in greater decreases. A study found that while heat treatment at 190°C for 9 hours reduced bending strength by 22.53% compared to control samples, treatment at 130°C for 3 hours resulted in bending strength comparable to untreated wood. In general, as modification intensity increases with higher temperatures and longer durations, mechanical properties like compression strength, bending strength, modulus of elasticity, hardness, and shear strength decrease (Gordiichuk, 2024).

H. Liu *et al.* (2022) examine that moderate TM of American alder (*Alnus rubra*) wood at 140°C for 4 to 13 hours had varying effects on its properties. The absolute dry density of TM wood exhibited a notable decrease with increasing treatment period, except for the group treated for 4 hours. After undergoing a treatment of 13 hours, Moderate TM significantly decreased wood residual stress by as much as 90.3%. Surprisingly, the mild TM had minimal impact on the mechanical properties of modulus of rupture (MOR) and modulus of elasticity (MOE). Nevertheless, the ability of wood to absorb moisture and take in water was greatly enhanced following a mild thermal modification, resulting in varying results based on the duration of the treatment.

In the study by M.H. De Paula *et al.* (2022), wood was treated at 180°C and 215°C for 20 and 40 minutes in a muffle furnace. The results showed that the basic density was not significantly affected, and there was a decrease in volumetric shrinkage, particularly in the most severe treatment (215°C for 40 minutes). The chemical analysis revealed a decrease in holocellulose and extractives content, leading to an increase in the percentage of lignin, especially in the most severe treatment. Importantly, the MOR and MOE did not change significantly after the short heat treatments of 20 and 40 minutes. This suggests that the mechanical properties were not compromised by the heat treatments, even at the higher temperature and longer duration.

Table 4 presents the values of the gluing resistance and wood failure referred to the feed speed. t-Test showed that between series of data there were essential differences ($p < 0.05$), implying a clear influence of the feed speed on the study parameters.

**Table 4.** Comparative results for the feed speed (t-Test)

| Feed speed [m/min] | Number of measurements | Gluing shear strength [N/mm$^2$] | | Wood failure [%] | |
|---|---|---|---|---|---|
| | | t | Sig. (2-tailed) | t | Sig. (2-tailed) |
| 3 | 88 | 41.58 | 0 | 53.99 | 0 |
| 10 | 88 | 42.43 | 0 | 44.94 | 0 |

**Source:** compiled by the authors

Table 4 compares the gluing shear strength and wood failure percentages at feed speeds of 3 m/min and 10 m/min, using t-tests to statistically analyse the differences. At a feed speed of 3 m/min, the average gluing shear strength was recorded at 41.58 N/mm$^2$ and the wood failure percentage at 53.99%, both showing statistically significant differences with a p-value of 0.000, indicating strong evidence against the null hypothesis. Conversely, at a feed speed of 10 m/min, the gluing shear strength slightly increased to 42.43 N/mm$^2$, while the wood failure percentage decreased to 44.94%, also demonstrating statistically significant results with a p-value of 0.000. This suggests that higher feed speeds may enhance shear strength slightly while reducing the incidence of wood failure, pointing to potential efficiency improvements in processing at increased speeds (Kozyar, 2023).

The study on thermally modified fir wood revealed that the modification temperature, feed speed, and gluing properties exhibited complex interactions. While temperature exhibited a near-significant effect on gluing shear strength, feed speed significantly influenced both shear strength and wood failure. The optimal performance was observed at 190°C, which balanced the strength and consistency of the material. Higher temperatures (220°C) resulted in decreased strength and altered failure patterns. Interestingly, faster feed speeds (10 m/min) generally led to improved shear strength and reduced of thermally modified wood. The analysis highlighted the critical role of feed speed and its interaction with temperature in determining material performance. These findings suggest that careful control of both thermal modification temperature and feed speed during processing can optimise the gluing properties and overall performance of thermally modified fir wood in various applications.

## Conclusions

The results of the tests showed that natural fir wood exhibits greater gluing shear strength than wood modified at high temperatures under atmospheric pressure. The shear strength undergoes a progressive decrease as the modification temperature increases, although this decrease is not statistically significant. This trend holds true for any feed speed used in planning the glued surfaces.

The wood failure does not present a linear relationship like strength. At 160°C, the failure is smaller than that of natural wood, while at higher temperatures, the opposite occurs. Even for wood failure, the temperature was statistically not significant. The decrease in the gluing quality of thermally modified wood is caused not only by the weakening of the mechanical strength of the wood but also by reduced adhesion due to insufficient glue permeability into the wood structure.

Regarding feed speed, a significant effect is noted only for gluing strength. For natural wood, a higher feed speed results in lower gluing strength compared to a lower speed. Interestingly, the opposite occurs with thermally modified wood. The lower reduction in gluing shear strength observed at higher modification temperatures for the feed speed of 10 m/min demonstrates the positive influence of high feed speeds on the gluing of thermally modified wood. This finding suggests that optimizing feed speeds could potentially mitigate some of the negative effects of thermal modification on gluing performance.

Future research should focus on exploring the underlying mechanisms responsible for the observed differences in gluing performance between natural and thermally modified wood. This could involve investigating changes in wood chemistry and microstructure at various modification temperatures and their relationship to adhesive penetration and bond formation. Additionally, studies examining a wider range of feed speeds and their interaction with different adhesive types could provide valuable insights for optimizing the gluing process for thermally modified wood in industrial applications.

## Acknowledgements

This research was funded by the Project "Evaluation of low-quality domestic timber using new gluing and modification techniques", in the framework of "Scientific and Technological Co-operation Programme" between governments of Albania and Kosovo.

## Conflict of Interest

The authors declare no conflict of interest.

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# Склеювання термічно модифікованої деревини сріблястої ялиці, струганої на горизонтально-фрезерному верстаті

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**Анотація**. Це дослідження було проведено з метою отримання інформації щодо якості склеювання деревини ялиці сріблястої (Abies alba Mill.), струганої з різною швидкістю подачі, після термічної модифікації. Було підготовлено чотири групи з шістнадцяти зразків ялиці, висушених на повітрі. Три групи були термічно модифіковані при різних температурах (160°C, 190°C і 220°C) протягом 3 годин. Послідовність процесів включала термічну модифікацію, стругання з двома швидкостями подачі (половина зразків зі швидкістю 3 м/хв, а інша половина зі швидкістю 10 м/хв), процес склеювання і, нарешті, проведення механічних випробувань для оцінки міцності на зсув і руйнування деревини. Міцність на зсув склеєного матеріалу поступово зменшувалася зі збільшенням температури модифікації для обох швидкостей подачі, причому зниження становило від 1,37 % до 14,63 % порівняно з натуральною деревиною. Руйнування деревини не показало лінійної залежності, зі зниженням при 160°C, але збільшенням при більш високих температурах порівняно з натуральною деревиною. Швидкість подачі мала значний вплив на міцність склеювання на зсув, причому вища швидкість подачі призводила до зниження міцності для натуральної деревини, але підвищувала міцність для термічно модифікованої деревини. Термічна модифікація деревини ялиці при температурі 220°C мала негативний вплив на міцність склеювання на зсув і руйнування деревини. Це було спричинено погіршенням компонентів деревини та зміною механічних властивостей. Результати цього дослідження дають важливі знання для вдосконалення процесу склеювання та встановлення відповідних параметрів для термічно модифікованої деревини ялиці. Цей вид деревини має потенційне застосування в деревообробній промисловості, зокрема у виробництві інженерних дерев'яних виробів

**Ключові слова**: деревина ялиці; термічна модифікація; склеювання; міцність на зсув; руйнування деревини

Received: 06.05.2024; Revised: 02.08.2024; Accepted: 15.08.2024

UKRAINIAN JOURNAL OF FOREST AND WOOD SCIENCE

Journal homepage: https://forestscience.com.ua/en
*Ukrainian Journal of Forest and Wood Science*, 15(3)

UDC 581.11(477.6)
DOI: 10.31548/forest/3.2024.148

# Comparison of transpiration activity of *Quercus robur* L. and *Acer campestre* L. trees under different conditions of moisture supply in the Viiskova ravine

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**Abstract.** Determining the role of trees in the water cycle and their impact on soil moisture and atmospheric humidity is crucial. This study aimed to investigate the patterns of leaf transpiration in *Quercus robur* and *Acer campestre* in a maple-oak forest under varying water supply conditions. The research was conducted in the lower third of the lower third of the north-facing slope and the middle third of the south-facing slope in the Viiskova ravine. A silvicultural and taxation survey of model trees was conducted on both sample plots, where the plantations are moderately dense. The diurnal course of transpiration patterns of these deciduous species was studied throughout the vegetation period. This physiological process reached its highest values in both species on the north-facing slope during the summer months, especially in *Quercus robur*. On the south-facing slope, in May and June, the average daily transpiration values in both species were almost indistinguishable. During the remaining months of the vegetation period, the intensity of water evaporation by *Quercus robur* leaves was statistically higher than that of *Acer campestre*. It was established that on the south-facing slope, under more arid conditions, this process is less active. This pertains to the daily transpiration loss of water by leaves per unit of their mass, monthly transpiration, and the intensity of this process per tree. The difference between the results of water loss by the leaves of a single *Quercus robur* and *Acer campestre* tree is significant and

***Suggested Citation:***

Bessonova, V., & Yakovlieva-Nosar, S. (2024). Comparison of transpiration activity of *Quercus robur* L. and *Acer campestre* L. trees under different conditions of moisture supply in the Viiskova ravine. *Ukrainian Journal of Forest and Wood Science*, 15(3), 148-164. doi: 10.31548/forest/3.2024.148.

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is attributed to the lower transpiration rate of *Acer campestre*, except in May and June under xerophytic conditions, as well as the smaller leaf mass of this species. Both *Quercus robur* and *Acer campestre* are hydrostable medium-transpiring species. The maple forest on the north-facing slope evaporates 30.6% more moisture per 1 ha per vegetation period than on the south-facing slope. The results obtained indicate that *Acer campestre* in a maple-oak forest, under fresh and dry forest-growing conditions, does not pose a significant competition for moisture for *Quercus robur* when they grow together. The results obtained can be used to develop effective forest management strategies in maple-oak forest

**Keywords:** lleaf water evaporation; common oak; field maple; forest-growing conditions; ravine forests

## Introduction

The increasing aridity of the climate and the decrease in water availability in certain areas lead to disruptions in the water regime of forest trees, including in Ukraine. This has a negative impact on their water and climate regulation functions. The water exchange of plants is influenced not only by environmental factors but also by the ratio of tree species in the phytocenosis. Competitive relationships between them can worsen the water supply of dominant species, reducing their resilience and longevity. *Quercus robur* is one such leading forest-forming species. Due to the discrepancy between the climatic conditions and the ecological requirements of this species in the steppe zone of Ukraine, oak phytocenoses are mainly concentrated in ravine forests. In this context, determining the water exchange of this dominant species and its companion species is relevant for the optimal construction of forest cenoses, and in natural forests, for regulating the density and ratio of species.

Considering water regime indicators in forestry practices and when creating forest plantations is a crucial factor that ensures the stability and balance of ecosystems. These characteristics are essential for enabling forest biogeocenoses to fully perform their vital resource functions. S.R. Weiskopf *et al.* (2020), investigating the impact of climate change on biodiversity and the ability of ecosystems to effectively perform their functions in the United States, concluded that the ability of forests to provide ecosystem services such as biodiversity habitat formation, climate mitigation, watershed protection, and erosion resistance is already gradually declining.

In a review article dedicated to analysing the existence of forests under drought and elevated carbon dioxide conditions, T.J. Brodribb *et al.* (2020) state the predicted further increase in the severity and frequency of droughts due to global warming. The review of the Fourth National Climate Assessment of the United States by A. Jay *et al.* (2018) consider the increased frequency of forest fires and outbreaks of diseases and pests in this context. Studies by A. Descals *et al.* (2023) using remote sensing methods have shown a progressive decline in the productivity of deciduous trees across Europe under drought stress, accompanied by early leaf shedding and the risk of tree death.

D. Ellison *et al.* (2017) emphasise the importance of forests in global hydrological and climate regulation, suggesting a transition from a carbon-focused approach to a water-regulating paradigm. G. Gao *et al.* (2022), assessing the contribution of transpiration to the magnitude of biogeocenoses evaporation and water cycle, indicated that woody plants replenish atmospheric moisture through evapotranspiration, promoting precipitation both locally and globally.

According to the IPCC's (Intergovernmental Panel on Climate Change) A1B scenario (moderate expected temperature rise with a decrease in precipitation) for most regions of Ukraine by the end of the century, significant warming and aridification are expected, along with a shift of moisture and heat supply zones towards the northwest. Consequently, I.F. Buksha *et al.* (2017), making a forecast for the existence and viability of *Quercus robur* on the plain part of Ukraine based on the A1B climate scenario, inform that already in the middle of the century, the area with conditions unsatisfactory for the existence of this species will cover 26% of the territory of Ukraine (in the south, partially in the centre and in the east), and the area of the zone unsuitable for its growth will be 56%. Under these conditions, oak stands will be preserved only locally in places with shallow groundwater, in floodplain areas, along rivers, and water bodies.

All of this underscores the relevance of studying the water exchange ecology of woody plants in phytocoenoses, with transpiration serving as a crucial indicator. However, these processes are mainly studied in trees within urban settings. For instance, D.V. Ganaba (2016) investigated the intensity of transpiration of woody plants in the dry period, which grew in different ecological zones of the Khmelnytskyi – within parklands and urban plantations. Nevertheless, research on water exchange issues in natural phytocoenoses of the steppe zone under current climate change conditions is practically absent.

The aim of this study was to compare the transpiration intensity of *Quercus robur* and *Acer campestre* leaves in a maple-oak forest under different water supply conditions and to determine the contribution of leaf mass of these tree species to water evaporation in these phytocenoses.

## Materials and Methods

The study was conducted in 2023 in a maple-oak forest on two experimental plots in the Viiskova ravine (Fig. 1), which belongs to a special geographical variant – the former rapids part of the Dnipro River. A.L. Belgard (1971) classified such ravines of this type as the southern outposts of natural ravine slope forests.

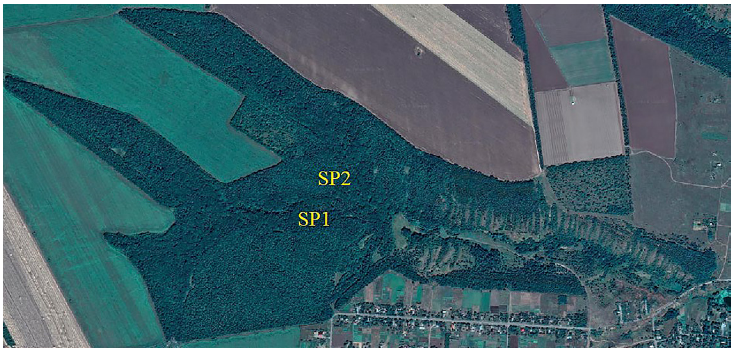

**Figure 1.** Map of the study area

**Note:** coordinates of the extreme points (48°11´08´´ N 35°07´45´´E; 48°10´41´´ N 35°10´12´´E)

**Source:** Google Maps

The research plots differed in location and hygrotopes. The first sample plot (SP1) is a maple-oak forest located on the lower third of a north-facing slope. The hygrotope is clay-loam soil ($CL_2$) (mesophytic, fresh soil). The second sample plot ($SP_2$) is a maple-oak forest located in the middle third of a south-facing slope. The hygrotope is $CL_1$ (xerophytic, arid). Both plots are characterised by atmospheric transit moisture. It should be noted that the south-facing slopes (light) and north-facing slopes (shadow) exposures differ in moisture and heat distribution. South-facing slopes warm up the most, receiving a greater amount of solar energy (Belgard, 1971). The subjects of the study were common oak (*Quercus robur* L.) and field maple (*Acer campestre* L.). The temperature and humidity of the air were measured using an electronic thermohygrometer TA-308 (Tcom, China). The values of these indicators are presented in Figure 2.

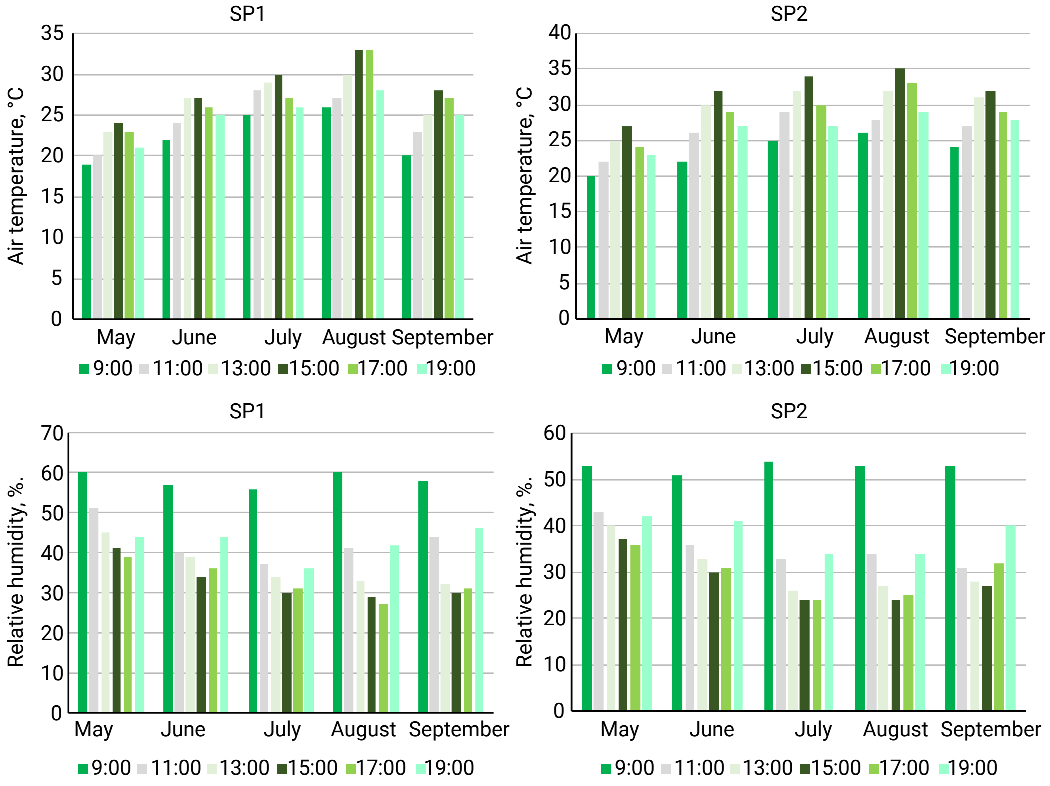

**Figure 2.** Temperature and relative humidity in the sample plots

**Source:** own measurements on the day of plant material collection

Plant material samples were collected using garden pruners from the southeast side of the middle part of the crown of the studied species during the vegetation period (May 15, June 21, July 14, August 16, and September 13) under identical lighting conditions. Leaves for determining the intensity of transpiration were plucked from branches of the same order of branching (third-fourth leaf from the base of the shoot of the current growth). The rapid weighing method according to Ivanov (Bessonova, 2006) was used with electronic scales TVE-0.21-0.001 (Technovagy, Ukraine). The experiment was conducted with five repetitions. The height of the trees was measured with an optical altimeter Suunto PM–5/1520 (Suunto, Finland), and their trunk diameter was measured with a calliper Codimex S-1 (Codimex, Poland). The leaf mass of the tree was established using the equation by M. Bibich (Urban ecology, 2017):

$$Y = -1.307 + 0.93x - 0.114x^2 + 0.01x^3,$$

where Y is the leaf mass, kg; x is the trunk diameter at a height of 1.3 m from the soil surface, cm.

The study was conducted in accordance with the ethical norms of the Convention on Biological Diversity (1992) and the Convention on the Trade in Endangered Species of Wild Fauna and Flora (1973). The results of the study were statistically processed using the standard software package IBM SPSS Statistics 22. A value of $P < 0.05$ was considered statistically significant.

## Results and Discussion

The stands on both sample plots are maple-oak forest of natural origin. The density of the plantations on the plots with different types of forest-growing conditions (FGC) was determined: they belong to the category of moderately dense (Table 1).

**Table 1.** Silvicultural and taxation characteristics of the plantations of the sample plots

| FGC | Stand composition | Species | $H_{avg.}$, m | $D_{avg.}$, cm | Stand density, units/ha |
|---|---|---|---|---|---|
| **SP1** | | | | | |
| $CL_2$ (mesophilic) | (Qu.ro)4(Ac.ca)6 | *Quercus robur* | 20.1 | 22.5 | 222 |
| | | *Acer campestre* | 16.5 | 17.4 | |
| **SP2** | | | | | |
| $CL_1$ (xerophilic) | (Qu.ro)3(Ac.ca)7 | *Quercus robur* | 18.8 | 21.4 | 251 |
| | | *Acer campestre* | 14.6 | 16.9 | |

**Note:** $H_{avg.}$ – the average height of the trees, $D_{avg.}$ – average diameter of the tree species in the sample plot
**Source:** developed by the authors

The basic taxonomic indicators of the model trees in the sample plots were determined since the value of the average diameter was used to calculate the transpiration parameters.

Leaf transpiration intensity is one of the most important indicators of plant water exchange. Studying this process in *Q. robur* leaves under mesophytic conditions ($CL_2$) showed that the patterns of the diurnal course of transpiration curves differ during the months of the study. In May, there is a significant increase in the intensity of transpiration evaporation of water from 9:00 to 13:00, after which the values remain almost unchanged until 15:00, followed by a decrease in activity. Lower values at 9:00 and 11:00, compared to the summer months, may be associated with high air humidity, which makes transpiration difficult. The same applies to the value of the process at 17:00, which is the lowest compared to all other months of the study, despite the moisture reserves in the soil. In June, the intensity of transpiration is expressed by a double-peaked curve, with peaks at 11:00 and 17:00, and with a minimum at 15:00. The onset of pronounced soil and air drought in July led to intensive evaporation of water already in the morning hours. The transpiration curve has two maxima: at 11:00 and 17:00. The highest values were recorded at 11:00 – 520 $mg \cdot g^{-1}$ of wet leaf mass, followed by a sharp drop in transpiration activity by 15:00 with the lowest values compared to other months of the study (245 mg·g$^{-1}$ of wet leaf mass). The second, smaller maximum of the diurnal course of transpiration in July occurs at 17:00. In September, the water evaporation by *Q. robur* leaves in the process of transpiration increases until 11:00, then there is no sharp change in the activity of this process. A significant decrease occurs at 19:00, as in all months of the study (Fig. 3).

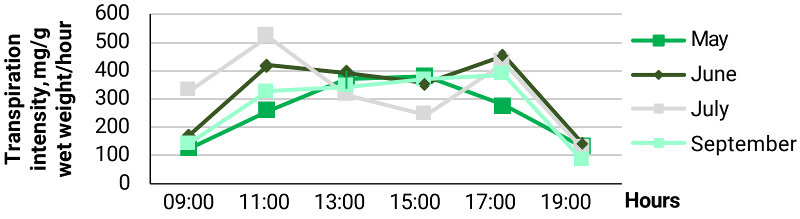

**Figure 3.** The diurnal course of transpiration of *Quercus robur* leaves under mesophylic conditions
**Source:** developed by the authors based on V.P. Bessonova *et al.* (2023)

The daily moisture expenditure by *Acer campestre* leaves in the process of transpiration under mesophytic growth conditions (north-facing slope) is the highest at 13:00 in May (Fig. 4). This is followed by a gradual decrease in the intensity of this process. In June, the daily fluctuations in transpiration activity are sharper. The maximum level of this process was recorded at 11:00. The second peak of water evaporation was determined at 17:00, which is 1.36 times smaller than the first peak. During the hottest hours (13:00 and 15:00), transpiration decreases, especially at 15:00 – by 1.82 times relative to the first maximum. The most significant fluctuations in water evaporation by *A. campestre* leaves were established in July. The diurnal course of transpiration in this month is expressed by a double-peaked curve, with maxima at 11:00 and 17:00.

Between these maxima, there is a significant drop in the intensity of this process, especially at 15:00, when the highest air temperature was recorded. In July, as in June, intensive water evaporation occurs already at 9:00 in the morning. The curve of the diurnal evaporation of water by *A. campestre* leaves in September differs from the curves of the summer months of June and July. As in *Q. robur*, there are no sharp changes in transpiration values from 11:00 to 17:00 (Fig. 4).

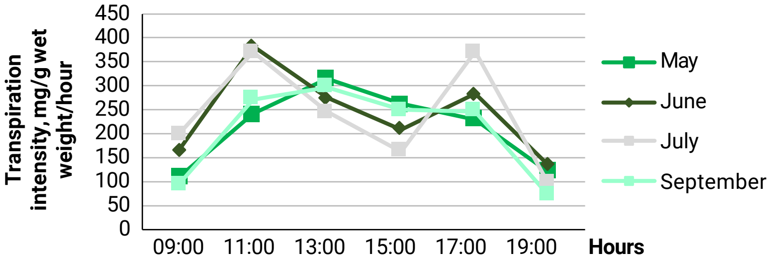

**Figure 4.** The diurnal course of transpiration of *Acer campestre* leaves under mesophytic conditions
**Source:** developed by the authors based on V.P. Bessonova *et al.* (2023)

The transpiration curves of the studied tree species in the maple-oak forest on the south-facing slope of the ravine (xerophytic growth conditions, $CL_1$) differ somewhat from those on the north-facing slope (mesophytic conditions, $CL_2$). In the spring month (May), the evaporation of water by *Q. robur* leaves increases significantly at 11:00 compared to the morning values (at 9:00), and then the intensity of its growth decreases. The most active transpiration occurs from 11:00 to 15:00, after which a decrease in this process is determined. More significant fluctuations in the level of transpiration of *Q. robur* leaves are observed in June. The curve reflecting the changes in the intensity of this process during the day is characterised by two peaks – at 11:00 and 17:00. A significant decrease in the activity of this process is noted at 15:00 (2.04 times relative to the first maximum) since this time is marked by the highest air temperature and low humidity. In July, the curve of the diurnal course of transpiration is similar to that in June, but the maximum values of the indicators at 11:00 and 17:00 are higher, as is the drop at 15:00. In September, a distinct increase in transpiration intensity is recorded at 11:00, with the value remaining almost at the same level at 13:00, followed by a decline at 15:00. A new rise in the evaporation of water by *Q. robur* leaves is observed at 17:00. This is followed by a significant decrease in the value of transpiration in the evening hours (Fig. 5).

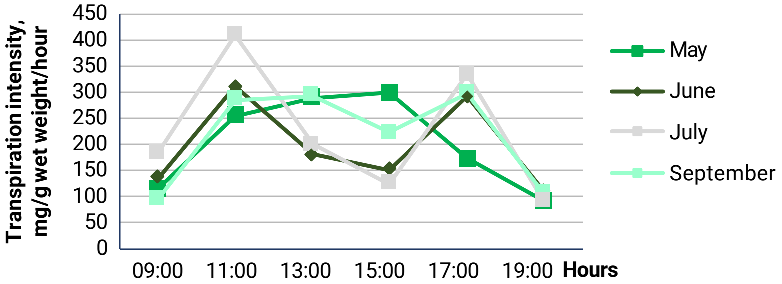

**Figure 5.** The diurnal course of transpiration of *Quercus robur* leaves under xerophytic conditions

**Source:** developed by the authors based on V.P. Bessonova *et al.* (2023)

The evaporation of water by *A. campestre* leaves in the maple-oak forest under xerophytic growth conditions (south-facing slope) gradually increases throughout the day until 15:00 in May. Then it remains at the same level with a sharp drop at 19:00. In the first summer month of June, a high intensity of transpiration is observed already in the morning – at 9:00. The curve of changes in the transpiration process in this month is double-peaked. The first peak occurs at 11:00 with insignificant changes in the indicator at 13:00, followed by a decline at 15:00. The second maximum, smaller than the first, is observed at 17:00. After that, the intensity of transpiration decreases.

The curve of the diurnal course of transpiration in July has a broken pattern with two maxima: a larger one at 11:00 and a smaller one at 17:00. A significant dip in the graph is observed between 13:00 and 15:00, which corresponds to the highest temperatures and the lowest relative humidity. Moreover, the transpiration values at these hours are the same. Apart from the morning (9:00) and evening (19:00) minima, the transpiration water loss curve in September is the highest level compared to the graphs in other months of the study (Fig. 6).

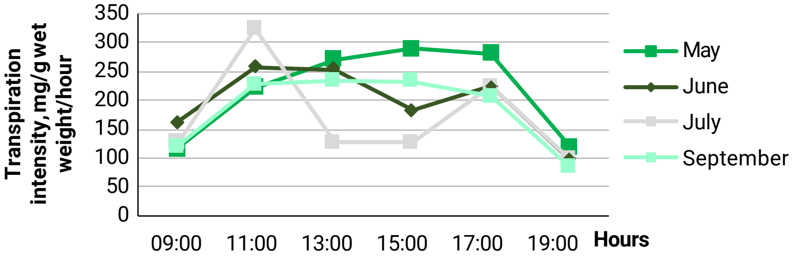

**Figure 6.** The diurnal course of transpiration of *Acer campestre* leaves under xerophytic conditions

**Source:** developed by the authors based on V.P. Bessonova *et al.* (2023)

The calculation of the average daily activity of water evaporation by the leaves of the studied tree species shows that the highest values are reached in both species on the north-facing slope in the summer months (Fig. 7). It should be noted that the higher average intensity of transpiration during the day is characteristic of *Quercus robur* leaves compared to the values of this process in *Acer campestre*.

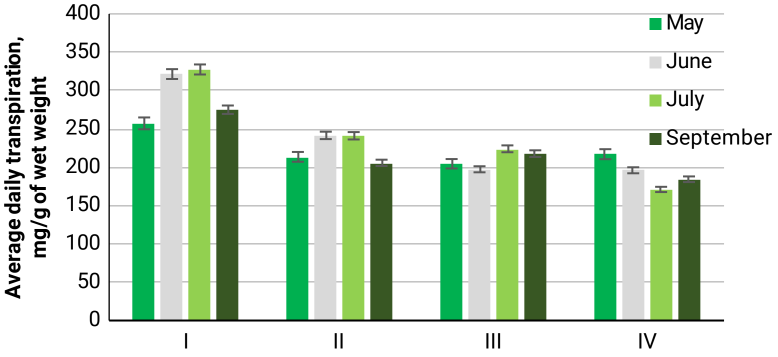

**Figure 7.** Average daily leaf transpiration of tree species under different forest growing conditions, mg·g$^{-1}$ wet weight

**Note:** I – *Quercus robur* on the north-facing slope; II – *Acer campestre* on the north-facing slope, III – *Quercus robur* on the south-facing slope; IV – *Acer campestre* on the south-facing slope

**Source:** developed by the authors

On the south-facing slope, the average daily transpiration values in both species are almost the same in May and June. Throughout the rest of the vegetation period, the intensity of water evaporation by *Quercus robur* leaves is statistically higher than that of *Acer campestre*. An analysis of the transpiration rates of *Quercus robur* in mesophytic ($CL_2$) and xerophytic ($CL_1$) growing conditions shows that this physiological process is 27.2% less active on the south-facing slope (CL1) compared to trees of the same species on the north-facing slope ($CL_2$).

For *Acer campestre*, this difference is 14.1%. The data obtained indicate the adaptive adjustment of *Quercus robur* to soil moisture deficit under more arid (xerophytic) conditions of SP2. A similar trend of change, but less pronounced, is also characteristic of *Acer campestre*. Table 2 shows the calculated transpiration rates of the studied tree species under different forest growing conditions – in fresh (SP1) and dry (SP2) maple-oak forest.

**Table 2.** Transpiration indicators of deciduous species in a maple-oak forest at different levels of moisture supply (2023)

| **Months** | **SP1 ($CL_2$)** | | **SP2 ($CL_1$)** | |
|---|---|---|---|---|
| | ***Q. robur*** | ***A. campestre*** | ***Q. robur*** | ***A. campestre*** |
| **Transpiration daily water loss by leaves, mg·g$^{-1}$*** | | | | |
| May | 2,880.6 | 2,391.2 | 2,290.4 | 2,430.4 |
| June | 3,600.8 | 2,704.8 | 2,209.8 | 2,195.2 |
| July | 3,668.0 | 2,699.2 | 2,508.8 | 1,915.2 |
| August | 3,080.0 | 2,303.8 | 2,438.2 | 2,064.2 |
| September | 3,071.2 | 2,301.7 | 2,421.3 | 2,079.9 |
| **Transpiration water loss by leaves per month, mg·g$^{-1}$** | | | | |
| May | 89,298.6 | 74,127.2 | 71,002.4 | 75,342.4 |
| June | 108,024.0 | 81,144.0 | 66,294.0 | 65,856.0 |
| July | 113,708.0 | 83,675.2 | 77,772.8 | 59,371.2 |
| August | 95,480.0 | 71,417.8 | 75,584.2 | 63,990.2 |
| September | 92,400.0 | 69,114.0 | 73,146.0 | 61,926.0 |
| **Water loss during transpiration by a tree per month, g** | | | | |
| May | 6,768,833.8 | 2,453,610.3 | 4,572,554.5 | 2,267,806.2 |
| June | 8,188,219.2 | 2,685,866.4 | 4,269,333.6 | 1,982,265.6 |
| July | 8,619,066.4 | 2,769,649.1 | 5,008,568.3 | 1,787,073.1 |
| August | 7,237,384.0 | 2,363,929.1 | 4,867,622.4 | 1,926,105.0 |
| September | 7,003,920.0 | 2,287,673.4 | 4,710,602.4 | 1,863,972.6 |
| **Water loss during transpiration by species per month from 1 ha, mm** | | | | |
| May | 59.6 | 32.9 | 34.3 | 39.9 |
| June | 72.1 | 35.9 | 32.0 | 34.9 |
| July | 75.8 | 37.1 | 37.6 | 31.5 |
| August | 63.7 | 31.7 | 36.5 | 33.9 |
| September | 61.6 | 30.6 | 35.3 | 32.8 |
| **Total, mm** | **332.8** | **168.3** | **175.7** | **172.9** |
| | **501.0** | | **348.6** | |

**Note:** * – the average weighted value of the period of the day during which water evaporates is 11.2 hours
**Source:** developed by the authors

As seen in Table 2, the overall transpiration water loss per unit leaf mass per day is greater in *Quercus robur* in all the months of the study at SP1. It decreases on SP2, with the difference between the indicators on the experimental plots growing more significantly in June and July. The daily water loss by the transpiring surface of *Acer campestre* is also greater under mesophytic growth conditions (SP1) than under xerophytic conditions (SP2), as is the case for *Quercus robur*, especially in June and July. However, under xerophytic conditions in May, when soil moisture is higher compared to the summer months, water loss by *Acer campestre* leaves is somewhat more significant on the $CL_1$ plot. The worsening of adverse hydrothermal conditions leads to an increase in the difference between the values of daily water evaporation by the transpiring leaf mass of *Quercus robur* and *Acer campestre*. The largest daily water loss by *Quercus robur* leaves on both experimental plots is observed in July, and for *Acer campestre* on SP1, it is in July and June, and at SP2, it is in May.

A similar pattern of water evaporation is characteristic of the results of monthly transpiration. Analysis of the data on the monthly water loss by leaf mass per tree shows the same pattern. More moisture is evaporated by both *Quercus robur* and *Acer campestre* under more favourable water supply conditions – mesophytic (SP2). However, the difference between the results of water loss by the leaves of a single *Quercus robur* tree is much greater than when calculating the total monthly transpiration loss per unit leaf mass. The difference in the values of this indicator between the studied tree species is especially large. Significantly less water is evaporated by the leaf surface of *Acer campestre*, which is due to both lower transpiration intensity compared to *Quercus robur*, except for May and June under xerophytic conditions, and lower leaf mass per tree.

The difference in water loss by leaves per hectare, taking into account the existing number of trees of each species, is quite significant between the species on SP1 on a monthly basis. It is the largest for *Quercus robur* and *Acer campestre* in the mesophytic maple-oak forest in July (Table 2). The quantitative indicators of water evaporation in the process of transpiration by *Quercus robur* leaves under mesophytic growth conditions (SP1) amount to 332.8 mm/ha, and for *Acer campestre* – 168.3 mm/ha. Under xerophytic conditions (SP2), these indicators are 175.7 and 172.9 mm/ha, respectively.

The leaves of one hectare of a *Quercus robur* plantation in a maple-oak forest on a shady slope (mesophytic conditions) evaporate 1.89 times more moisture than on a sunny slope (xerophytic conditions), even though the number of trees of this species in mesophytic conditions is only 1.17 times higher. Water loss by *Acer campestre* leaves on both the north-facing slope (SP1) and south-facing slope (SP2) is not significantly different, although the number of trees is 1.32 times higher on SP2. It should be noted that on SP1, the leaves of *Quercus robur* trees transpire 1.97 times more water per hectare than *Acer campestre*.

However, in the xerophytic maple-oak forest, the difference between the species in terms of the amount of water evaporated per hectare is small. This is explained by the fact that the ratio between the species on SP1 is 1.45 (formula of composition (Qu.ro)4(Ac.ca)6, *Acer campestre* prevails), and on SP2 – 2.33 ((Qu.ro)3 (Ac.ca)7), and the stand density in the mesophytic maple-oak forest is 222 trees/ha, and 251 trees/ha in the xerophytic one. These ratios lead to nearly equal transpiration water losses per hectare by maple and oak, which is not favourable for *Quercus robur* in such a mixed plantation on the south-facing slope. These results indicate the importance of regulating the ratio between the species to obtain optimal water evaporation indicators for the stand.

According to the data presented in Figures 3-6, the highest values of water evaporation by both *Quercus robur* and *Acer campestre* leaves in the process of transpiration are usually observed around 11:00. In the hottest summer months, this indicator decreases significantly when the highest temperatures and lowest relative air humidity are observed, and in the afternoon hours it again increases to a second maximum at 17:00. Thus, during the period of the highest temperatures, the intensity of transpiration decreases significantly, which indicates the ability of the studied plant species to regulate water exchange. Therefore, both species belong to the hydrostable category according to the classification given by W. Larcher (1978).

Such a decrease in transpiration activity under unfavourable hydrothermal conditions is a valuable adaptation that has developed in the process of evolution. However, on the other hand, a similar decrease in water evaporation by leaves leads to their overheating, which is very negative for plants with low heat resistance, as indicated by I.A. Vasilenko *et al.* (2017), who studied the drought resistance and water exchange of trees and shrubs.

According to their observations on the transpiration in twenty shelterbelt species regarding the intensity of this physiological process under the conditions of the Derkulskyi steppe, L.A. Ivanov *et al.* (1952) divided woody plants into three groups: strongly transpiring, moderately transpiring, and weakly transpiring. Based on the obtained indicators of the average daily intensity of leaf transpiration of *Quercus robur* and *Acer campestre* (Figs. 3-6), they can be classified as species with moderate water evaporation. The boundaries for this group, according to L.A. Ivanov *et al.* (1952), are 163-298 $mg \cdot g^{-1}$ wet mass/hour under very dry conditions of the Derkulskyi steppe and 374-480 $mg \cdot g^{-1}$ wet mass/hour in the Forest-Steppe zone, where the amount of precipitation is 1.5 times higher (420 and 650 mm, respectively).

V.I. Lyalko *et al.* (2012) studied the transpiration water losses of plant communities using remote methods and their combination with statistical estimates of water evaporation by certain phytocenoses over the vegetation period. As the authors emphasise, transpiration is one of the components of the water balance of the territory and is comparable in level to river runoff. In this case, the value of this process depends on the type of vegetation. In their article, researchers provided data on water evaporation by oak stands in the Donetsk and Kirovohrad Regions, which reach 405 and 520 mm per year, respectively. The data obtained in this study on the loss of water in the process of transpiration by the leaves of trees in a maple-oak forest over five months of vegetation were: under mesophytic conditions, evaporation amounted to 501.0 mm, and under xerophytic conditions, it was 348.6 mm. A.P. Krivoruchko (2019) determined the intensity of transpiration both in a mixed stand of *Quercus robur* and *Quercus rubra* with their ratio of 3:7 and in the growth of these species in single-species groups in the steppe zone of Ukraine. However, since the object of study was 11-year-old trees, the value of water evaporation by the leaf surface of these plantations per hectare cannot be used for comparison with the data obtained by the authors.

As can be seen from Figure 7, the average daily intensity of transpiration of *Quercus robur* and *Acer campestre* leaves under different hydrothermal conditions on the north-facing and south-facing slopes of the ravine Viiskova is higher under mesophytic conditions. Yu.L. Celniker (1958), studying the water regime of leaves of woody plants of the steppe zone, found that under drought conditions, moisture loss decreases with increasing stress of environmental factors. However, the study of the water-salt regime of plants and their communities under drought conditions of the Caucasus by I.N. Beydeman (1957) indicates that under optimal soil moisture, the intensity of plant transpiration increases simultaneously with increasing air dryness and temperature.

The value of water loss per day in the process of transpiration by the leaves of a maple-oak forest per 1 hectare in July-September under mesophytic conditions is within 3.64-3.07 mm, and under xerophytic conditions, it ranges from 2.23 to 2.24 mm. M. Landblad & A. Lindroth (2002) analysed the transpiration of forest stands depending on weather, soil moisture and stand characteristics (pure and mixed with *Pinus sylvestris*, *Picea abies*). They observed a wide range of values for this process (from 0.95 to 4.64 mm per day). The authors found that the average transpiration values for different stands varied from 1.30 to 4.64 mm per day during July-September.

As mentioned above, when the main and companion species grow together, the question arises of their competition for such resources as water supply and soil fertility. The optimal combination of tree species in a phytocenosis determines not only the environmental impact of forests, but also their productivity, stability, and longevity. V.I. Karpenko (2013), studying the forestry properties of such companion species for *Quercus robur* as *Acer platanoides*, *Carpinus betulus*, and *Tilia cordata* in mixed stands of the Forest-Steppe zone, found that it is little leaf linden that does not displace the roots of common oak from the upper soil layers to the lower ones, therefore it is its best companion species. N.P. Shpak *et al.* (2017) studied forest plantations of *Quercus robur* with the participation of several companion species in their composition. As the authors proved, the presence of *Tilia cordata* increases soil fertility and stand productivity. Moreover, the root systems of *Tilia cordata* and *Quercus robur* complement each other in the rhizosphere, promoting better growth of both species. *Sorbus torminalis* also possesses such properties in relation to *Quercus robur*.

Several researchers draw attention to the need to consider the role of certain tree species in the water cycle of forest ecosystems and their optimal combination, taking into account possible competition for water. Thus, H. Asbjornsen *et al.* (2007) underscore the importance of evaluating the interception of water by *Ulmus americana* when grown together with *Quercus macrocarpa* in American oak forests. Such studies are especially relevant in the context of the arid climate of the Ukrainian steppe. In particular, several authors highlight competitive relationships between *Quercus robur* and *Fraxinus excelsior*. For example, A.A. Silina (1958), analysing the influence of some tree species on the transpiration of others when grown together in the Steppe zone of Ukraine, found that under drought conditions *Fraxinus excelsior* is a dangerous competitor for *Acer platanoides* and, especially, for *Quercus robur*.

The studies of V.I. Obraztsova & N.P. Kotsyubinskaya (1976) also showed that the intensity of transpiration of *Fraxinus excelsior* on experimental plots with different water supplies in the riparian and floodplain oak forests of the steppe zone of Ukraine is higher than that of *Quercus robur*. Competition for water can lead to the suppression of the growth processes of tree species and, in general, to a decrease in the stability of phytocenoses. However, during the study of forest plantations of *Quercus robur* with the participation of native and introduced fast-growing species, Yu.D. Katsulyak (2009) found that in dry and fresh maple-oak forest with a share of *Fraxinus excelsior* not exceeding 30% with its even distribution across the area, exacerbation of competition with *Quercus robur* for soil-hydrological resources is not observed.

According to the results presented in this article, under mesophytic growth conditions, the intensity of transpiration of *Quercus robur* leaves is higher than that of *Acer campestre* during the vegetation period. In xerophytic conditions, it is also higher in July and September. In May, the transpiration values for *Acer campestre* are slightly higher, and in June they are almost the same for both species (Figs. 3-7).

Thus, *Acer campestre* leaf surface evaporates significantly less water, due to both lower transpiration intensity compared to *Quercus robur*, except for May and June under xerophytic conditions, and lower leaf mass per tree. Under mesophytic conditions, *Quercus robur* evaporates 1.97 times more per 1 ha than *Acer campestre*. It is also necessary to take into account the ratio of species on the sample plots. On the north-facing slope, there are 1.45 times more

*Acer campestre* individuals than *Quercus robur*, and on the south-facing slope, there are 2.33 times more. This leads to the fact that the total evaporation of water by *Acer campestre* plants under xerophytic conditions reaches almost the same values as those of *Quercus robur*, which further increases the stress of the water regime. The data obtained indicate the need to take this fact into account when constructing plantations in the steppe zone.

Therefore, *Acer campestre* is one of the optimal companion species for *Quercus robur*, since it belongs to the group with moderate transpiration activity and does not act as an aggressive competitor in water interception, given the appropriate ratio of trees in the plantation. It should be noted that *Acer campestre* thrives well in the second tier of oak phytocenoses, improving forest growing conditions in oak forests, as it belongs to acidifying species. In addition, as noted by V.E. Svyrydenko *et al.* (2004), the leaf litter of *Acer campestre* contributes to soil acidification, which benefits the growth of *Quercus robur*, a species with high mycotrophic requirements. A slightly acidic environment is optimal for mycorrhizal symbiosis.

According to P.F. Ffolliott (2008), who studied water evaporation by oak plantations (*Quercus emoryi*) on watersheds in New Mexico, USA, transpiration data are important for developing a general water budget for the studied ecosystems. This information, in combination with existing precipitation and water flow measurements, will contribute to a more accurate assessment of the ecosystem's water balance.

The data obtained as a result of the research carried out by the authors will bring greater clarity to understanding issues related to water use by both dominant and companion species in the maple-oak forest under different water supply conditions. The discussion outcomes indicate that the impact of companion species on the physiological characteristics of *Quercus robur*, including its water regime, requires further investigation.

## Conclusions

The stands on both sample plots are natural maple-oak forests, characterised by an average stand density of trees. The curves reflecting the diurnal course of the transpiration pattern of *Quercus robur* under mesophytic conditions in June and July have a double-peaked character with maxima at 11:00 and 17:00. In the rest of the vegetation period, the graphs have a smoother character. A similar pattern is observed in the fluctuation of water evaporation activity by *Acer campestre* leaves under mesophytic conditions. Under insufficient water supply (xerophytic conditions) in June and July, both species also show two peaks in the diurnal course of transpiration activity at the same hours of the day. In *Acer campestre*, the maximum intensity of transpiration is observed at 15:00 in May, its values approaching the value of July evaporation activity, which was recorded at 11:00.

Average daily leaf transpiration activity is maximum for both species on the north-facing slope under mesophytic conditions ($CL_2$) in the summer months, especially for *Quercus robur* compared to the values of this process in *Acer campestre*. On the south-facing slope under xerophytic conditions ($CL_1$) in May and June, the average daily transpiration values of both species are practically the same. Throughout the rest of the vegetation period, the intensity of water evaporation by *Quercus robur* leaves is statistically higher than that of *Acer campestre*.

Analysis of the diurnal course of transpiration of the studied species under the conditions of hygristotopes $CL_2$ and $CL_1$ showed that these woody plants are hydrostable and, according to the value of average daily activity of water evaporation, belong to the moderately transpiring species. On both sample plots with different levels of plant water supply, *Quercus* *robur* leaves, for the most part, transpire more actively than *Acer campestre*, although it was found that in some measurement hours, opposite results were observed.

The intensity of leaf transpiration of *Quercus robur* in the maple-oak forests under the conditions of hygristopos $CL_1$ in more arid growing conditions is less active (by 27.2%) than under conditions of better water supply ($CL_2$). This can be considered an adaptive adjustment of *Quercus robur* to soil moisture deficit. This is less characteristic of *Acer campestre*. On the north-facing slope, the average transpiration during the growing season is higher than on the south-facing slope. The maple-oak forest on the south-facing slope evaporates 30.6% less per 1 ha during the growing season than the stand on the north-facing slope under conditions of better water supply.

The results obtained indicate that *Acer campestre* in maple-oak forests under the conditions of fresh ($CL_2$) and dry ($CL_1$) hygristotopes will not be a serious competition for water for *Quercus robur* when they grow together. However, an analysis of the research results shows that it is important to consider the quantitative ratio between the species, especially in xerophytic growing conditions, in order to create favourable conditions for water exchange in oak stands. The prospect of further research is the analysis of morphophysiological indicators of different tree species when they grow together in phytocenoses under the influence of unfavourable hydrothermal conditions, which is typical for the summer months in the steppe zone of Ukraine.

## Acknowledgements

None.

## Conflict of Interest

None.

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# Порівняння активності транспірації дерев *Quercus robur* L. і *Acer campestre* L. в різних умовах забезпечення вологою балки Військова

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**Анотація.** Важливим є визначення ролі дерев у водному циклі та їх вплив на вологість ґрунту й атмосферну вологозабезпеченість. Метою роботи було дослідити особливості перебігу транспірації листків *Quercus robur* і *Acer campestre* у пакленових дібровах за різних умов водозабезпечення. Дослідження проводилося в нижній третині схилу північної і середній третині схилу південної експозицій у байраці Військовий. Проведено лісівничо-таксаційне обстеження модельних дерев на обох пробних площах, насадження яких є середньогустими. Вивчено денний хід транспірації цих листяних порід протягом вегетації. Найбільших значень даний фізіологічний процес набуває в обох видів на схилі північної експозиції у літні місяці, особливо у *Quercus robur*. На схилі південної експозиції у травні і червні середньодобові значення транспірації в обох порід майже не відрізняються. Протягом решти місяців вегетаційного періоду інтенсивність випаровування води листками *Quercus robur* статистично вища, ніж у *Acer campestre*. Встановлено, що на схилі південної експозиції у більш посушливих умовах зростання дерев даний процес перебігає менш активно. Це стосується транспіраційної втрати води листками за день у розрахунку на одиницю їх маси, щомісячної транспірації й інтенсивності цього процесу у перерахунку на дерево. Відмінність між результатами втрати води листками одного дерева *Quercus robur* і *Acer campestre* є істотною і обумовлена як нижчим рівнем транспірації *Acer campestre*, за винятком травня і червня за ксерофільних умов, так і меншою масою листків цього виду. Як *Quercus robur*, так і *Acer campestre* є гідростабільними середньотранспіруючими породами. Пакленова діброва на схилі північної експозиції у перерахунку на 1 га за вегетаційний період випаровує вологи на 30,6 % більше, ніж на схилі південної. Одержані результати свідчать, що *Acer campestre* у пакленових дібровах за свіжих і сухих лісорослинних умов не виступає серйозним конкурентом за вологу для *Quercus robur* при їх сумісному зростанні. Отримані результати можуть бути використані для розроблення ефективних стратегій лісового господарювання в пакленових дібровах

**Ключові слова:** випаровування води листками; дуб звичайний; клен польовий; лісорослинні умови; байрачний ліс

Received: 17.04.2024; Revised: 10.07.2024; Accepted: 15.08.2024

UKRAINIAN JOURNAL OF FOREST AND WOOD SCIENCE

UKRAINIAN JOURNAL OF FOREST AND WOOD SCIENCE

Journal homepage: https://forestscience.com.ua/en
*Ukrainian Journal of Forest and Wood Science*, 15(3)

UDC 630:796.5
DOI: 10.31548/forest/3.2024.165

# Sustainable development of forest parks for active recreation: A balance between nature conservation and physical education

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**Abstract.** The study aims to comprehensively assess the negative impacts of various activities carried out by visitors to natural areas, including forest parks, on ecosystems. The research methodology included an analysis of forest park ecosystems Gotova-Dangel and Logara forest parks, monitoring ecosystem changes, which provided objective data on the impact of human activity. The study developed recommendations aimed at minimising the negative effects of these activities on the environment. The main results of the study demonstrated that walking leads to soil compaction, which in turn hurts water circulation and aeration of soil layers. This phenomenon can also cause damage to rare species of plants and trees that are vulnerable to changes in their natural environment. In addition, cycling causes soil erosion, which leads to the destruction of vegetation, which in turn negatively affects the environmental sustainability of the region. This can create conditions for the degradation of natural ecosystems and a decrease in biodiversity. Camping causes pollution of the area, including dumping garbage and other waste, which leads to a decrease in the number of animals living in forest environments, with serious consequences for the ecological balance and conservation of wildlife. The findings highlight the need to introduce clearly defined trails for pedestrian traffic, create specialised bicycle routes, and develop environmentally responsible camping practices. This will significantly reduce the negative

***Suggested Citation:***

Brovina, F., & Sallaku, D. (2024). Sustainable development of forest parks for active recreation: A balance between nature conservation and physical education. *Ukrainian Journal of Forest and Wood Science*, 15(3), 165-179. doi: 10.31548/forest/3.2024.165.

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impact on the forest ecosystem. The research is relevant for the conservation of biodiversity as well as for maintaining the ecological balance in forest parks, which is critical for the sustainable development of natural resources and the preservation of the environment for future generations

**Keywords:** ecology; biodiversity; ecosystem; nature protection; leisure

## Introduction

With the growing interest in active recreation in natural environments, research on how different types of physical activity affect the ecosystems of forest parks is relevant. Forest parks perform a critical ecological function, providing habitats for many species of flora and fauna, as well as supporting important ecological processes such as climate and water balance regulation. However, outdoor activities can have significant negative impacts on these systems, including damage to vegetation, changes in animal behaviour and soil erosion.

The problem is a lack of information on how different types of outdoor activities, such as hiking, cycling and camping, affect forest ecosystems. There is a need for a detailed analysis of this impact and the development of effective strategies to minimise the negative consequences.

Existing studies focus on the overall impact of recreational activities on nature. They demonstrated that outdoor activities could have both positive and negative effects on ecosystems. The problem of a clean and sustainable environment in forest areas, in Lithuania and Turkey, was studied by A. Atalay *et al*. (2024). Their study highlights the impact of recreational activities on the ecological state of forest areas and offers solutions to reduce the negative effects. G. Ospan *et al*. (2024) assessed the impact of winter tourism on natural heritage in Kopaonik National Park, focusing on the negative effects of winter tourism and developing a strategy for the conservation of natural resources. T. Tapps & M.S. Wells (2024) analysed the basics of recreational activities and leisure time, providing basic concepts for understanding the development of recreational areas and their sustainable management.

The potential of tourism and recreation in rural areas of Kazakhstan was analysed by K. Saparov *et al*. (2024). They addressed the development of sustainable tourism and the use of natural resources in these regions. K.G. Kling (2024) addressed the balance between accessibility and conservation in protected areas. The study highlighted the challenges that arise when trying to provide access to natural areas while maintaining their value. B.M. Akgül & S. Karaküçük (2024) studied the concepts of eco-recreation and its application to create sustainable recreational environments. The work covered the theoretical and practical aspects of integrating ecology and recreation.

A systematic review of tourism in European national parks was conducted by D.S. Donici & D.E. Dumitras (2024). They studied different management models and the impact of recreational activities on natural ecosystems. A. Melaku & J. Pastor Ivars (2024) examined cultural ecosystem services in urbanised sacred forests. This study focuses on how such forest areas support human well-being through cultural and ecological services. G. Lukoseviciute *et al*. (2024) studied participation in the development and management of ecocultural routes. The study suggests methods for integrating cultural and environmental aspects into tourist routes. V. Ristić *et al*. (2024) assessed the importance of forest ecosystems for the development of nature-based tourism in the Fruska Gora National Park. The study highlighted the importance of forest areas for eco-tourism and their management.

Despite the existing research covering various aspects of outdoor activities, there are still many gaps in understanding the specific mechanisms of the impact of different types of outdoor activities on individual ecosystem elements. This is especially true for activities such as camping, hiking and cycling routes, which can have both positive and negative environmental impacts. For instance, the long-term effects of camping on biodiversity, which is critical for maintaining ecological balance, and soil erosion in specific types of forest environments are not well determined. Studying these aspects can help to develop more effective strategies for managing natural resources and preserving ecosystems.

The study aims to examine the impact of three types of active recreation: hiking, cycling and camping – on forest ecosystems. Study goals:

1. Analysis of the impact of hiking on the flora and fauna of forest parks, including a study of plant and animal species affected by hiking, including changes in the number and range of different species and an overall assessment of biodiversity.

2. Assessment of the impact of cycling on biodiversity and determining the impact of cycling on forest park ecosystems.

3. Development of practical recommendations to reduce the negative impact of camping by studying its effects on forest park ecosystems and creating approaches to managing outdoor recreation for biodiversity conservation.

## Materials and Methods

The study, which was conducted from June to September 2024, covered a wide range of aspects of human interaction with the natural environment. The main locations for field research were two forest parks: Gotova-Dangel Forest Park and Logara National Park (Albania). The selected areas not only represent samples of various forest ecosystems but also provide unique conditions for studying the impact of various types of active recreation, such as hiking, cycling and camping, on these ecosystems.

The research began with careful planning and methodology development, including the definition of the main objectives and the choice of data collection methods. Forest, in particular trees, were emphasised as their condition is critical to the health of the ecosystem.

To assess the undergrowth and dead wood, methods were used to identify the physical condition of the trees and their biomass. This information became the basis for understanding the impact of human activity on tree cover. In particular, the assessment of tree health, growth and density helped to determine how active recreation contributes to or hinders forest conservation and restoration.

Observing the number of young trees and the presence of dead wood was another important element of the study. These observations were used to assess the natural regeneration of the tree cover and identify negative impacts caused by active recreation, such as trampling on young plants or reducing the amount of dead wood, which is critical for nourishing the soil and creating an environment for new plants.

Phytoindication was used as a method of assessing environmental stress. Assessment of tree health, including damage to leaves, roots and trunks, served as an indicator of the impact of human presence and physical activity, including cycling. This was used to identify how human activity can lead to a deterioration in tree health and the overall condition of the forest.

An integrated approach to assessing the condition of trees and their ecosystems provided a detailed understanding of the impact of outdoor activities, which became the basis for making decisions on the conservation and restoration of forest resources.

For a more detailed analysis, information on the level of soil erosion and vegetation condition was collected. This process involved the use of modern methods, such as Geographic Information System (GIS) and Global Positioning System (GPS), which were used to accurately determine erosion processes and their impact on the environment. GPS and GIS were also used to monitor the condition of trees and their location, which is an extremely important aspect of modern forest management, as it allows not only to pinpoint the exact location of each tree but also to assess its condition, identify diseases, pests or other factors that may threaten its life. This will help to create a detailed map of damaged or degraded areas, which in turn will allow for more efficient management of forest parks. The collected data was used as a basis for further analysis and development of recommendations for the conservation of natural resources and ecosystem restoration.

SPSS and Excel statistical packages, which provided powerful tools for detailed statistical processing and analysis of the results, were used. These software tools were used not only to evaluate the results of the study with high accuracy but also to identify certain patterns and trends that could be useful for further research and practical application of the data obtained. The collected materials were carefully processed and analysed to assess the impact of outdoor activities on forest ecosystems.

The study was conducted following the ethical standards set out in the Convention on Biological Diversity (1992) and the Convention on International Trade in Endangered Species of Wild Fauna and Flora (1973). The study employed a systematic approach that provided clear data on the impact of outdoor activities and contributed to the development of effective strategies for the conservation and enhancement of forest ecosystems.

## Results

Active recreation in forest parks, while enjoying the outdoors and communicating with nature, can have a significant impact on the ecological balance of these unique ecosystems. Walking leads to soil compaction, which negatively affects the root system of plants and can cause erosion. Cycling, in turn, causes damage to vegetation and disturbance of natural habitats, as cyclists often ride on paths that are not intended for this purpose. Camping causes pollution of the territory if waste disposal rules and proper care of campfires are disregarded.

Hiking was one of the most common forms of active recreation in forest parks, as people could enjoy nature, maintain physical activity and improve their psycho-emotional state. However, despite all the positive aspects, even such seemingly safe activities can have negative consequences for vegetation and the ecosystem as a whole. The constant pressure on the trails caused by the large number of visitors led to soil compaction, which made it difficult for new plants to grow, as the roots could not penetrate the soil freely, which negatively affected their nutrition and development. Visitors trampled on rare plant species: marsh orchid "*Dactylorhiza sphagnicola*" – "Gotha-Dangel", forest lily "*Lilium martagon*" – Logara Park, which not only caused their damage but may also lead to their extinction in the future. Therefore, awareness of the impact of human activity on the environment is necessary, as well as rules of conduct in natural areas to preserve their uniqueness and biodiversity.

The impact of hiking on animals was complex and manifested in both direct and indirect forms. The presence of people and the sounds they made in the study area caused stress in wildlife, which in turn led to changes in their behaviour. For instance, common beavers *(Castor canadensis)* were forced to leave their usual habitats, which will harm their reproduction and survival. The golden eagle *(Aquila rapax)* changed its nesting sites and flight periods in response to human activity (Table 1). This manifested itself in the fact that they began to hide earlier than usual or changed their traditional migration routes, which led to a violation of the ecological balance.

**Table 1.** Rare species affected by outdoor activities and other human factors

| Plant/animal species | Place of residence | Cause of threat |
|---|---|---|
| Marsh orchid (*Dactylorhiza sphagnicola*) | Rivers and reservoirs | Trampling by pedestrians |
| Forest lily (*Lilium martagon*) | Forest areas | Injuries during outdoor activities |
| Common beaver (*Castor canadensis*) | Rivers and reservoirs | Stress from human activity |
| Golden eagle (*Aquila rapax*) | Mountainous areas | Change of nesting sites |
| Orchid (*Orchis papilionacea*) | Forest areas | Trampling and loss of environment |
| Grass cat (*Felis silvestris*) | Forested areas | Destruction of the environment, hunting |
| Red lizard (*Lacerta agilis*) | Dry and rocky locations | Habitat loss and human impacts |
| Mountain frog (*Bufo viridis*) | Wet landscapes | Water pollution and climate change |

**Source:** compiled by the authors

In Gotova-Dangel and Logara parks, flora and fauna responded to human activity by reducing available food resources and altering the natural environment. For instance, pedestrian activity in the Gotova-Dangel park has led to the destruction of vegetation, which is an important source of food for many animal species. Observations in these natural reservoirs have shown that birds and small mammals tend to leave areas where trails are active more often, indicating that they are adapting to changes in the environment caused by human activity. This phenomenon requires careful study as it may have long-term implications for biodiversity and ecosystems.

The impact of human activity on the condition of trees in forest parks is a significant and complex aspect of the ecological balance. Intensive hiking, cycling and camping, which have become popular forms of recreation, can cause trampling of the soil around the root system of trees. This, in turn, harms their stability and development, as tree roots need healthy soil to receive nutrients and water (Table 2).

**Table 2.** Results of the assessment of the condition of trees in the forest parks Gotova-Dangel and Logara under the influence of active recreation

| Location | Condition of trees (general) | Damage detected (leaves, trunk, roots) | Number of young trees | Presence of dead wood | Level of environmental stress |
|---|---|---|---|---|---|
| Forest Park Gotova-Dangel | Satisfactory | Damage to leaves and trunks | High (21-50%) | Low | Moderate |
| Logara National Park | Weak | Significant damage to all parts | Average (6-20%) | Average | Proficiency |

**Source:** compiled by the authors

Frequent human intervention in natural processes can cause mechanical damage to tree trunks, leaves and roots. Such damage leads to a decrease in the overall health of trees, which makes them more vulnerable to diseases, pests and other stressors. Situations are particularly dangerous when human activity is accompanied by the use of heavy machinery or equipment, which can lead to even more serious damage.

The presence of litter and pollution caused by human activity can have a significant impact on soil and water quality. Contaminated soils can interfere with the normal growth of trees, as harmful substances can enter the root system, preventing the absorption of essential elements. Campfire activities can also inflict burns to trunks or roots, which in turn reduces their viability.

The spread of invasive plant species is another serious consequence of human activity that can reduce the competitiveness of native trees. Invasive species often grow faster and take up the space needed for the roots of native plants to develop, which leads to a change in the natural balance of the ecosystem.

Thus, active recreation, if left unchecked, can cause significant changes in the condition of trees and the overall ecosystem of forest parks. Natural resource preservation efforts are necessary, as the health of forest parks directly affects the quality of life of people who use these natural spaces.

Measures to minimise impacts on natural ecosystems are essential to preserve biodiversity and maintain environmental health. Creating and maintaining clearly defined trails is an important step in reducing the area that visitors can ravage. This not only helps to limit access to sensitive ecosystems but also provides conditions for revegetation, which helps to preserve the natural environment. Marked trails also make it easier for visitors to find their way around, reducing the risk of accidental damage to the vegetation. Educating visitors about the importance of protecting vegetation and wildlife is a key element in raising environmental awareness. Information boards can include data on vulnerable species, and ecosystems and their role in maintaining the ecological balance. This can significantly reduce accidental damage and encourage visitors to follow the rules of behaviour in nature, which in turn will help preserve natural resources for future generations.

The study found that cycling had more serious consequences for the flora than walking. This is determined by the wheels of the bicycles having a significant impact on the soil surface, digging it up, destroying natural vegetation and contributing to increased erosion. Such activities led to the destruction of the root system of plants, which in turn hurt the ecosystem. The study determined that the speed of cyclists led to the widening of paths and the emergence of new trajectories, which further damaged the vegetation. This put additional pressure on the natural environment, as the new routes passed through sensitive ecosystems, disrupting their integrity and functioning. Thus, it is necessary to address the environmental impact of cycling and seek ways to reduce its negative impact on the environment.

Cycling has a significant stressful impact on wildlife, which is an important aspect to account for. The sharp noise generated by cycling and the high speed of the cyclists caused the animals to feel fear and anxiety, which led to the sudden abandonment of their natural habitats and negatively affected their social structures. In Logara Park, the animals were forced to search for new areas to live in, which disrupted their usual migration routes and interaction with other members of the species. Such changes have had far-reaching consequences for the ecosystems in which these animals live and have affected their ability to survive.

Measures to minimise the impact on the natural environment are highly relevant in the context of the growing use of bicycles and outdoor activities. Establishing designated bicycle routes that do not intersect with hiking trails can significantly reduce the negative impact on vegetation and fauna. This avoids conflicts between pedestrians and cyclists, which in turn reduces the risk of damage to natural ecosystems. Individual routes can also be designed to address the natural features of the area, which will ensure the preservation of biodiversity and maintain ecological balance. Installation of soft surfaces for bike paths, such as rubber tiles or natural materials, can significantly reduce soil erosion and plant damage. Not only do these coatings reduce the negative impact on the environment, but they also increase comfort and safety for cyclists. In addition, the use of specialised equipment to maintain and service the tracks can ensure their durability and reduce the need for frequent repairs, which will also have a positive impact on the environmental situation in the region.

Camping has long-lasting and significant effects on the flora of forest parks, which requires attention from conservation organisations and recreationists. The establishment of camps leads to the destruction of vegetation, which occurs not only under the tents but also near fires where people cook and relax. Emissions from campfires, such as ash and smoke, as well as waste left behind after camping, pollute soil and water, which negatively affects vegetation and the ecosystem.

The study determined that camping had the greatest impact on flora among the three main outdoor activities, such as hiking and cycling. The presence of the camps has led to severe damage to vegetation, including the destruction of plant roots, which are important for maintaining biodiversity, and soil erosion, which leads to a loss of fertility. This highlights the need to comply with environmental regulations and practices when camping to minimise the negative impact on the environment.

Camping has caused significant stress to wildlife in the Gotova-Dangel and Logara parks for several reasons, including the sounds of campfires and the smells of cooking. These factors forced the animals to abandon their natural habitats as they perceived human activity as a threat. As a result, the animals in the Gotova-Dangel park changed their diets as their usual food sources became less accessible or dangerous.

Camping also had a significant impact on the fauna in the study areas, leading to a decrease in the number of different animal species and changes in their behaviour. Animals began to avoid areas with high human activity (Table 3). These changes in behaviour had long-term consequences for ecosystems, as the natural relationships between species were disrupted. Therefore, it is necessary to address environmental aspects when organising a campsite and choose places that have minimal impact on wildlife.

**Table 3.** The impact of outdoor activities on ecosystems

| Type of active recreation | Impact on vegetation | Impact on animals | Impact on trees |
|---|---|---|---|
| Hiking | Soil compaction, trampling on rare species | Stress, behavioural change | Mechanical damage, reduction in the number of young trees |
| Cycling | Vegetation damage, erosion | Stress, change in migration routes | Root damage, reduced tree health |
| Camping | Pollution, destruction of vegetation | Stress, diet change | Burns of trunks, destruction of young plants |

**Source:** compiled by the authors

Measures to minimise the environmental impact of camping are highly important for the preservation of natural ecosystems. Selecting designated camping areas not only helps to reduce accidental damage to vegetation but also helps to preserve the natural landscape. Such sites are usually equipped following environmental standards, which reduces the likelihood of negative environmental impact. Thanks to this, visitors can enjoy nature without harming the local flora and fauna. The ban on the use of open fires is an important step in the fight against environmental pollution and the destruction of vegetation. Instead, the mandatory use of portable cooking stoves not only reduces the risk of forest fires but also reduces emissions of harmful substances into the air. Such rules keep the territory clean and preserve natural resources for future generations.

One of the most promising approaches is the strategy of creating ecological corridors. Ecological corridors are stretches of land that provide a link between separated natural environments, allowing wildlife to migrate and exchange genetic material. This process is critical to maintaining biodiversity as it helps to strengthen species populations, prevents inbreeding and increases the overall resilience of ecosystems to environmental change. Ecological corridors can be created in a variety of ways, including by preserving natural forest belts that function as natural arteries for wildlife movement. The process of planting trees and other plants between separated forest patches is also relevant, helping reconnect isolated animal populations. This, in turn, not only ensures the conservation of biodiversity but also improves the overall health of ecosystems, which has a positive impact on the climate and quality of life.

Restoration of natural habitats is an important process that involves not only reconstruction but also restoration of ecological functions in destroyed or degraded areas. This process may include a range of measures, such as planting native plants, controlling invasive species, and creating appropriate conditions for the restoration of natural populations of flora and fauna. Monitoring the ecosystem is also an important aspect to ensure the effectiveness of the measures taken.

The biotechnical measures implemented as part of the restoration include planting to stabilise the soil, which is critical to preventing erosion. Plants, especially those with a strong root system, can penetrate deep into the soil, which helps to hold it in place and reduce the risk of erosion. Grasses and shrubs can be successfully planted on slopes and along rivers, which not only stabilises the soil but also improves the water balance in the region. Thus, restoration of natural habitats is a key element in the conservation of biodiversity and environmental sustainability.

Barriers, such as windbreaks, are significant in reducing wind speeds, which in turn significantly reduces the risk of soil erosion. These forest belts not only block strong winds but also help to retain moisture in the soil, which is also critical for maintaining fertility. They can be particularly effective in agricultural areas where intensive farming can lead to significant soil loss.

Additional solutions that can be implemented to combat erosion include the creation of water catchment systems that control water runoff, reduce the risk of flooding and erosion, and conserve water resources. Catchment systems can include drainage channels, ponds and other structures that help regulate the water balance in the soil.

Soil reclamation is another important aspect that involves restoring the fertility and structure of soils that have been damaged by various factors such as construction, intensive rest or aggressive agricultural practices. This process can include the application of organic fertilisers, which improve the biological activity of the soil, and liming, which helps to neutralise acidity and improve nutrient availability. In addition, covering soils with mulch is an effective method for retaining moisture, preventing weeds and improving overall soil quality. All these measures contribute to the restoration of the ecosystem and ensure the sustainability of agricultural production.

Natural methods of ecosystem restoration, including the use of native plant species, are extremely effective in quickly restoring degraded areas. The use of native plants that are adapted to specific environmental conditions contributes to revegetation and biodiversity, as these species provide habitat for local animals and microorganisms. Natural processes, such as the accumulation of leaves and branches, are key in supporting the natural regeneration of ecosystems. These organic materials serve as a natural fertiliser and help to retain moisture in the soil, which in turn promotes the growth of new plants.

Managing forest resources is a complex and multifaceted process that involves regular monitoring of forest health, controlling pest and disease populations, and maintaining an optimal balance between timber harvesting and forest regeneration. This involves keeping records of the state of forests, conducting research to identify potential threats and developing strategies to overcome them. Harvesting should be planned in a way that does not disrupt the ecological functions of forests, which includes considering seasonality, biological cycles of native species, and the preservation of key ecosystem services provided by forests, such as air purification, water balance regulation, and soil conservation. Therefore, an integrated approach to forest management ensures their resilience and ability to recover in the face of climate change and anthropogenic pressures.

The involvement of local communities in forest management, as well as educational campaigns, are crucial steps that can significantly raise public awareness of the importance of ecosystem conservation. Community involvement in management processes helps to create a more responsible attitude towards natural resources, which can lead to improved forest parks. Informing the public about the environmental consequences of human activity and encouraging responsible behaviour can have a significant positive impact on the preservation of the natural environment. This includes training and active participation in nature conservation activities. The conservation and restoration of natural ecosystems in forest parks requires a comprehensive approach that includes not only practical strategies but also active community participation in these processes.

The use of various technologies and methods, such as environmental monitoring systems, restoration of the natural environment, and implementation of sustainable management practices, was used to maintain biodiversity, prevent soil erosion, restore damaged areas, and ensure a healthy forest environment for future generations. Therefore, the integration of knowledge, technology and active participation of society are key elements in achieving effective forest management and conservation of natural ecosystems.

## Discussion

The study confirmed the importance of integrating environmental and sustainable approaches into the planning and management of natural areas. The results showed that effective management of recreational resources can significantly improve the ecological balance and ensure sustainable development. This is especially true for areas with a high tourist load, where it is necessary to find a balance between nature conservation and meeting the needs of visitors.

The impact of recreational practices on nature and tourist experience was studied by G. Lukoseviciute *et al*. (2024). They found a positive impact of organised recreational activities on environmental sustainability and showed that well-planned recreational areas contribute to nature conservation. The results confirm these findings but also reveal additional negative aspects, such as the potential stress on ecosystems from overuse. This indicates the need for more detailed management of recreational areas. V. Voronkova *et al*. (2024) focused on the creative development of the concept of green ecotourism as a factor of sustainable development, noting the positive impact of ecotourism on the conservation of natural resources. The study determined a significant potential for ecotourism in sustainable development, which is confirmed by the findings, but showed that the economic impact of ecotourism may be greater than expected, which may require a review of economic strategies in green tourism. N. Bhatt *et al*. (2024) investigated the relationship between cultural ecosystem services and traditional ecological knowledge for forest management in the Indian Himalayas. They determined the importance of cultural aspects in ensuring effective forest management. This study confirms the importance of cultural and social factors in biodiversity conservation but reveals additional regional differences in natural resource management that require further research.

Sustainable development of rural areas in protected areas, in Strandzha (Bulgaria), was studied by S. Petrova *et al*. (2024), pointing out that the integration of environmental and social factors is critical for effective natural resource management. These findings confirm the importance of integrating environmental and social aspects but additionally reveal specific challenges for rural areas in other regions that may require a different approach. D.E. Jacob *et al*. (2024) analysed the use of bioindicators for planning recreational areas and the balance between nature and human activity. They emphasised the importance of monitoring environmental indicators to maintain the balance. This is in line with results of this study and confirms the importance of bioindicators, but the study also found that current methods could be improved to improve the accuracy of the assessments.

The potential of recreational areas in the Karagel National Park, Turkey, was assessed by N. Doygun *et al*. (2020), determining that properly planned recreational areas can significantly increase tourist attractiveness. The results confirm this conclusion but also show that some planning methods may need to be adapted to different geographical conditions. I. Koshkalda *et al*. (2023) studied the prospects for the development of recreational lands, emphasising the importance of long-term planning to achieve sustainable development. These results are consistent with these conclusions but also demonstrate the need for more comprehensive management approaches that address specific regional characteristics. In turn, X. Luo *et al*. (2024) analysed tourist preferences and willingness to pay for biodiversity and recreational management in Wuishan National Park, China. They found that investments in biodiversity conservation are highly valued by tourists. This study confirms this trend but also found that cultural and economic aspects may influence willingness to pay, which requires further analysis. The study of the impact of land use planning and green environmental services on sustainable development, through the development of hiking trails, was conducted by G. Kyriakopoulos (2023). It was found that well-planned trails can have a positive impact on environmental sustainability and sustainable development. This study confirms the importance of green spatial elements but also shows that their effectiveness can vary depending on local conditions and needs.

Y. Tao & P.-H. Lin (2023) analysed the sustainable development of cultural and creative parks using knowledge mapping methods. They identified the key factors that influence the success of such parks. This study determined similar success factors but also showed that there is a need for a more detailed study of specific cultural aspects to improve the effectiveness of parks. The synergistic development of the sports industry and the ecological environment of urban parks was studied by L. Manrong & M. Zhang (2023). The study determined that the integration of both aspects can provide significant benefits for the urban environment. The study confirms these findings but additionally reveals that to achieve optimal results, it is necessary to account for the specifics of the urban context. T. Grindsted *et al*. (2023) studied the integration of sustainable tourism into the development of natural parks, identifying conflicts between different interests. It is noted that sustainable management requires a balance between environmental and tourism requirements. This study confirms these conclusions but also shows that having clear management strategies in place can make it much easier to achieve a balance.

The synergy between environmental sustainability and the development of the eco-hospitality industry in the Miyun-Beijing area was studied by Z. Qilun *et al*. (2023). They found that effective management can ensure the harmonious development of both aspects. The study found similar results but also highlighted the need to address local conditions to improve the integration of environmental and economic factors. M. Jalinik & P. Selwesiuk (2023) analysed the development of tourism and recreational infrastructure in forest districts of Poland, identifying the need to improve existing infrastructure solutions. The results confirm these findings, demonstrating that current infrastructure solutions can be improved to better meet the needs of tourists and local communities. The impact of environmental education on primary education, with a focus on physical activity and sports programmes in the natural environment, was studied by M. Santos-Pastor *et al*. (2022). The results showed a positive effect on sustainable development through the integration of physical activity, which is in line with the original findings, which confirm the importance of environmental education but also show the need to adapt programmes to specific conditions and cultural contexts to maximise their effectiveness.

The study by M. Phil (2022) demonstrated the link between ecotourism and sustainable development, as well as strategies for balancing economic growth, socio-cultural development and nature conservation. It was found that ecotourism can be an effective tool for achieving sustainable development. This study confirmed these conclusions but also pointed to the need for a more detailed analysis of the specific conditions and factors that may affect the implementation of ecotourism strategies. D. Aly & B. Dimitrijevic (2022) applied a systematic approach to the sustainable management of urban public parks, by studying management strategies. The results confirmed the effectiveness of the systemic approach in improving the sustainable development of parks. The findings are consistent with this approach but highlight the need to consider additional socio-economic factors to improve management strategies.

The assessment of natural and recreational resources of the Akmola region for sustainable tourism development was carried out by K. Yegemberdiyeva *et al*. (2020). The study determined that the resources can be effectively used for tourism development while adhering to sustainable practices, which confirms the conclusions drawn, demonstrating the importance of resource assessment for the successful implementation of sustainable tourism. G. Rodríguez-Loinaz & I. Palacios-Agundez (2024) investigated how environmental services education can improve students' arguments in support of nature conservation and sustainable development. The results indicated a positive impact of such education on students' attitudes. This study confirmed these results but also highlighted the need to integrate environmental topics into various aspects of the curriculum. M. Trudeau (2024) examined the concept of "naturalness" in Calgary's natural playgrounds, focusing on sustainable development and environmental education. The study determined that natural playgrounds could promote greater environmental awareness. This supports the findings, demonstrating the positive impact of such innovations on children's learning and environmental awareness.

The analysis of the research results showed that they are in line with international trends in environmental education, sustainable tourism development and natural resource management. However, it is necessary to address the specifics of local conditions to achieve the best results.

## Conclusions

The study determined that different types of active recreation have different degrees of impact on forest park ecosystems. Hiking causes soil compaction and damage to rare plants, cycling leads to soil erosion and destruction of vegetation, and camping leads to pollution and a decrease in the number of animals. Trees are also significantly impacted by outdoor activities: mechanical damage to the root system and trunks can cause a decrease in tree health and increase their vulnerability to pests and diseases. Qualitative indicators include a decrease in biodiversity and deterioration of vegetation.

To reduce the negative impact of outdoor activities on ecosystems, it is recommended to introduce clearly defined trails for pedestrians, develop special bicycle routes that reduce soil erosion, and introduce environmentally responsible camping practices, such as limiting the size of camping areas and providing garbage collection. Further research should focus on analysing long-term changes in forest park ecosystems under the influence of different types of outdoor activities, evaluating the effectiveness of the implemented recommendations in reducing the negative impact and developing new methods for a more detailed study of the impact of outdoor activities on different ecosystems.

The study has some limitations, including geographical ones: it covered only certain forest parks, namely Gotova-Dangel and Logara, which may not reflect the full impact of outdoor activities in other regions. In addition, methodological limitations include impact assessments based on surveys and observations, which may not fully capture all aspects of environmental change.

The study confirmed that active recreation has a significant impact on the ecosystems of forest parks, which varies depending on the type of activity. The results obtained indicate the need to develop and implement effective measures to reduce the negative impact and conserve biodiversity. Further research should focus on long-term effects and improved management practices to improve the ecological status of forest areas.

## Acknowledgements

None.

## Conflict of Interest

None.

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# Сталий розвиток лісопарків для активного відпочинку: баланс між охороною природи та фізичним вихованням

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**Анотація.** Метою дослідження є комплексна оцінка негативного впливу різних видів діяльності відвідувачів природних територій, зокрема лісопарків, на екосистеми. Методологія дослідження включала аналіз лісопаркових екосистем лісопарків Готова-Дангел та Логара, моніторинг змін екосистем, що дозволило отримати об'єктивні дані про вплив людської діяльності. За результатами дослідження були розроблені рекомендації, спрямовані на мінімізацію негативного впливу цієї діяльності на навколишнє середовище. Основні результати дослідження продемонстрували, що ходьба призводить до ущільнення ґрунту, що, в свою чергу, шкодить циркуляції води та аерації ґрунтових шарів. Це явище також може завдати шкоди рідкісним видам рослин і дерев, які є вразливими до змін у своєму природному середовищі. Крім того, їзда на велосипеді спричиняє ерозію ґрунту, яка призводить до знищення рослинності, що, в свою чергу, негативно впливає на екологічну стійкість регіону. Це може створити умови для деградації природних екосистем та зменшення біорізноманіття. Кемпінги спричиняють забруднення території, в тому числі скидання сміття та інших відходів, що призводить до зменшення кількості тварин, які живуть у лісовому середовищі, з серйозними наслідками для екологічної рівноваги та збереження дикої природи. Результати дослідження підкреслюють необхідність запровадження чітко визначених стежок для пішохідного руху, створення спеціалізованих велосипедних маршрутів та розвитку екологічно відповідальних практик кемпінгу. Це дозволить значно зменшити негативний вплив на лісову екосистему. Дослідження є актуальним для збереження біорізноманіття та підтримання екологічної рівноваги в лісопарках, що є критично важливим для сталого розвитку природних ресурсів та збереження довкілля для майбутніх поколінь

**Ключові слова:** екологія; біорізноманіття; екосистема; охорона природи; відпочинок

# УКРАЇНСЬКИЙ ЖУРНАЛ ЛІСІВНИЦТВА ТА ДЕРЕВИНОЗНАВСТВА

*Науковий журнал*

**Том 15, № 3. 2024**

Заснований у 2010 р. Виходить чотири рази на рік

Оригінал-макет видання виготовлено
у відділі науково-технічної інформації
Національного університету біоресурсів і природокористування України

**Відповідальний редактор:**
Г. Івченко

**Редагування англомовних текстів**:
С. Воровський, К. Касьянов

**Комп'ютерна верстка**:
О. Глінченко

Підписано до друку 15 серпня 2024 р. Формат 70*100/16
Умов. друк. арк. 14,6
Наклад 50 прим.

**Адреса видавництва**:
Національний університет біоресурсів і природокористування України
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# UKRAINIAN JOURNAL OF FOREST AND WOOD SCIENCE

*Scientific journal*

**Volume 15, No. 3. 2024**

Founded in 2010. Published four times per year

The original layout of the publication is made in the Department of Scientific
and Technical Information of National University of Life
and Environmental Sciences of Ukraine

**Managing Editor:**
H. Ivchenko

**Editing English-language texts**:
S. Vorovsky, K. Kasianov

**Desktop publishing:**
O. Glinchenko

Signed for print of August 15, 2024. Format 70*100/16
Conventional printed pages 14.6
Circulation 50 copies

**Editors office address**:
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https://forestscience.com.ua/en