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Influence of urban environment factors on morphometric parameters and accumulation of secondary metabolites in *Cercis canadensis* L. and *Cercis siliquastrum* ‘Alba’

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Abstract. Consideration of the role of green spaces in urban landscaping is extremely important, as they not only decorate the urban landscape, but also effectively reduce air pollution, regulate the microclimate and play an important role in improving the ecology and quality of life of residents. The purpose of the study was to determine the influence of urban environmental factors on the development and secondary metabolism of plants of the genus *Cercis* L. Plants growing in Kyiv (Ukraine) under conditions with different air humidity, anthropogenic load, and excess or lack of insolation were selected for the study. Plant growth processes were studied by morphometric parameters of annual shoots of *Cercis siliquastrum* 'Alba' and *Cercis canadensis* L. growing under different conditions. Morphometric methods, fluorescence microscopy, high-performance thin-layer chromatography and regression analysis were used in the study. The research data show that insufficient sunlight has a negative impact on shoot growth. The specificity of the phenolic profiles that can be used to distinguish between the species *Cercis canadensis* L. and *Cercis siliquastrum* 'Alba' was established. The principal component analysis confirmed that phenolic profiles depend on habitat conditions and affect plant growth and development. The Gaussian model was used to analyse the growth dynamics of annual shoots during the growing season, which allowed us to describe the specifics of internode formation during the growing season quite accurately. This model allowed us to detect the phenomenon of the last internodes falling off at the end of the growing season, which caused the deviation of the morphometric parameters of metameres from the normal distribution along the time axis. Anatomical studies confirmed that the separation of one or more of the last internodes was due to active corking of the internal tissues of the stem, blocking of the xylem and formation of a separating layer, which led to the fall of the shoot tip. This phenomenon shows signs of plant adaptation to low temperatures in winter. The tops of the shoots often do not have time to lignify and accumulate the required amount of cryoprotectants. With the formation of a separating layer, the available energy resources are redistributed to the lateral buds, which receive the necessary resources to prepare for the winter period and provide new growth in the next growing season. The adaptive potential of the two species of the genus *Cercis* L. confirms the prospects of their use in urban ecosystems, which can positively affect the conservation of biodiversity in general

Keywords: Judas-tree; environmental factors; green spaces; flavonoids; adaptation

Introduction

Green spaces in the urban greening system play a crucial role in the landscape and architectural, sanitary and hygienic, utilitarian and decorative, and other aspects of urban autecological relations. In particular, all green spaces reduce the level of gas and dust pollution, improve the microclimate by reducing the ambient temperature and increasing humidity, but different species cope with these tasks in different ways, so the question arises of the correct selection

of plants for urban landscaping in accordance with their environmental characteristics.

Due to climate change and a significant increase in anthropogenic impact, it is necessary to expand the range of planting materials when creating urban plantings. As noted by N. Seyidođlu Akdeniz (2020), the use of plants of the genus *Cercis* L. for urban landscaping with white, pink, and purple colours gives a sense of calm, continuity and vitality, which, in turn,

plays an important role in the recreation of urban populations.

Results of the study by N. Nuzhyna *et al.* (2022) on determining plant drought resistance, based on the indicators of leaf water content and moisture loss per unit time, indicate that *Cercis canadensis* L. is quite drought-resistant. The paper reveals new aspects of plant adaptation to changing environmental conditions, and considers strategies for plant survival in a rapidly changing climate. According to A. Nejad *et al.* (2018), lead exposure at a dose of 30 mg/l had a negative effect on the development of *C. siliquastrum* L.: the area of the leaf blade, the length of shoots, and the water content in the leaves decreased. However, this effect was offset by the use of nitrates (100 mg/l). These results indicate the importance of studying plant interactions with toxic metals and possible measures to reduce their exposure. According to F. Vignoli *et al.* (2021), the use of lawns alone reduces the temperature of the asphalt surface by 0.5°C, and in combination with trees and shrubs – by about 0.9°C, which reduces the negative impact of “heat islands” in the urban environment. In addition, such an ecosystem approach to the arrangement of lawns, trees and shrubs contributes to improving air quality and the overall urban climate. Green spaces help absorb water and reduce the risk of flooding, helping to create a more sustainable and environmentally balanced environment. These positive properties of green spaces confirm the importance of their implementation for achieving sustainable development and improving the quality of life in cities.

Moreover, according to H. Bahri (2021), concentration of flavonoids in flowers of *Cercis siliquastrum* L. decreases as they develop, and the content of terpenes, on the contrary, increases, which may indicate changes in secondary metabolism depending on the phase of plant development. These detected changes in the chemical composition of flowers of *Cercis*

siliquastrum L., in particular, reduction in the concentration of flavonoids and increase in the content of terpenes may also be of practical importance in the context of using these plants in landscape design or urban landscaping, based on their characteristics and adaptive properties. Given that changes in secondary metabolism may be associated with growth and development phases, further study of these mechanisms may help develop strategies to optimise growing conditions of *Cercis siliquastrum* L. to increase the biological activity and stability of these plants in various environmental conditions.

The study by A. Delbari *et al.* (2019) on the absorption of cadmium and lead by the roots of two plant species of the genus *Cercis* L. helped to identify the difference between them in resistance to soil contamination with toxic metals. It is evident that *Cercis siliquastrum* L. exhibit various reactions to the presence of these toxic metals, which may be of practical importance for their use in phytoextraction or phytostabilisation programmes of contaminated soils. Consideration of these interactions can be important for sustainable management of the urban environment and the effective use of plants in phytoremediation processes.

The purpose of the study is to investigate the bioecological features of plants of the genus *Cercis* L. and the correlation between morphometric and biochemical parameters.

Materials and Methods

The research was conducted between January 2023 and September 2023.

Conditions for the growth of research objects. The selected research objects were located in Kyiv, in particular, in the Shevchenkivskiy district (Fig. 1). The city’s climate is moderately continental, with mild winters and rather hot summers. The average temperature in July and January was +22°C and -2.8°C, respectively (Osadchyy *et al.*, 2013).

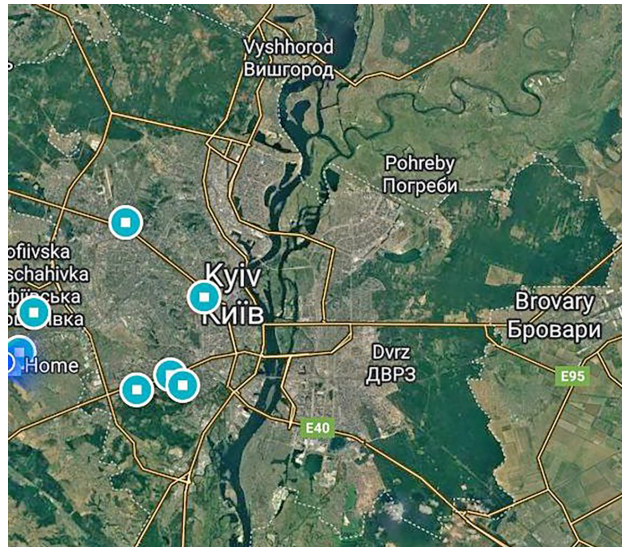


Figure 1. Layout of *Cercis L.* plantations in Kyiv

Source: compiled by the authors

The habitats of all plants can be conditionally divided according to the influence of external factors, such as air pollution, solar insolation, and soil salinity. For example, plants growing in the O.V. Fomin Botanical Garden were exposed to an average level of insolation (the amount of direct sunlight is about 6 hours per day) and air pollution, and the absence of soil salinity. Trees growing near the Beresteyska metro station had a high level of insolation (direct sunlight for about 10 hours a day) and were exposed to high levels of air pollution because they were located on the southern border of the Nyvky park. The plants growing on Tabirna Street were in shady conditions (the amount of direct sunlight was about 3 hours per day). The level of salinity was determined conditionally, depending on the distance of plants from pedestrian paths or highways. In particular, the plants growing in the park on Kirponos Street were characterised by a high level of insolation and soil salinity, as the plants grew in close proximity to the roadway and pedestrian path.

During the survey of plants of the genus *Cercis L.*, their condition was evaluated on a 5-point scale for assessing the condition of woody plants in outdoor plantings according to the method (Kuznetsov et al., 2000):

- ◆ 5 points (trees without suppressed growth, with a full leaf surface);
- ◆ 4 points (trees with growth that generally correspond to the norm and with approximately 20-25% of the inactive surface);
- ◆ 3 points (trees with weakened growth, which have about 50% of the inactive leaf surface);
- ◆ 2 points (trees with suppressed growth, the growth rate of current growth is almost nonexistent, have about 75-80% of the inactive leaf surface);
- ◆ 1 point (dead and drying, without current growth of trees with 100% inactive leaf surface).

Morphometric method. The analysis of morphometric parameters of shoots was carried out to assess the features of plant growth

processes depending on the growing conditions. Sampling was carried out in 5 localities. A total of 15 plants were used in the experiment. The length and diameter of internodes of annual shoots of 14 *C. canadensis* L. plants and shoots of 1 *C. siliquastrum* 'Alba' plant (n = 75) were measured.

Secondary metabolite profiling method. The separation of substances was performed by high-performance thin-layer chromatography (HPTLC) on Silicagel G 60 (Merck) plates in a solvent system: ethyl acetate-formic acid-acetic acid-water (v/v/v/v – 100:11:11:25). The resulting chromatograms were treated with 0.5% NP reagent in ethyl acetate, followed by treatment with 1.0% PEG (polyethylene glycol) 400 and heating at 90°C for 1 min. Flavonoids and other polyphenols on the chromatogram were detected in ultraviolet light (λ max = 365 Nm). The R_f (retention index) values of individual compounds were determined photodensitometrically using the Sorbfil TLC Videodensitometer computer programme.

Autofluorescence of shoot tissues was studied on an inverted microscope using a multichannel fluorescent imaging system (EVOS FL System, ThermoFisher Scientific, USA).

Method of statistical data processing. The measurement results are presented as the average value \pm standard error ($x \pm SE$). The significance of the difference ($p < 0.05$) between the obtained data was determined by variance analysis (one-way ANOVA) using Tukey's post-hoc test in the XLSTAT software suite (Addinsoft Inc., USA, 2010). Principal component analysis (PCA) and cluster analysis were performed in the XLSTAT software suite. Sigma Plot 12.0 (Systat Software, Inc.) was used for regression analysis.

Object of study – the object of study is the external state of plants *C. canadensis* L. and *C. siliquastrum* 'Alba' and their sensitivity to urban environmental factors. The study was conducted in compliance with the Convention on Biological Diversity (1992) and the Convention

on the Trade in Endangered Species of Wild Fauna and Flora (1973).

Annual shoots were collected from plants growing within the city of Kyiv. Sample preparation included cleaning of dirt and removal of unnecessary plant residues, followed by determining metric parameters (internode length and diameter). The parameters were measured using a caliper and the results were recorded in Microsoft Excel, followed by analysis of the data.

Results

Cercis canadensis L. – a tree up to 18 m high, with a spreading crown and a black and grey crust, sometimes it is a large shrub, which makes it attractive and versatile in terms of use in landscape compositions (Fedorovskyi *et al.*, 2013). Young shoots are reddish-brown. The leaves are cordate and rounded, 6-12 cm wide. Like the European species, it blooms before the leaves open in May. Flowers are pink to purple in colour, 1.0-1.2 cm long, in bunches on branches or on trunks (cauliflory – development of flowers from dormant buds on the trunk), very decorative (Domshyna & Shcherbak, 2015). Its natural habitat is North America. It most often grows on rich soils in lowlands and near marshes, and is moisture-loving. It is found in undergrowth, in valleys on the edges, in sparse forests. In the conditions of Kyiv, it regularly flowers and bears fruit (Kalinichenko, 2003; Zayachuk, 2014)

The general condition of the plantings varies: the condition of the plantings growing near the Beresteyska metro station was approximately 35 years old and rated at 4 points (dry branches, trunk damage or stunted development); trees growing on Tabirna Street were approximately 15-20 years old and rated at 3 points; the condition of plantings growing on Kirponos Street and the territory of the Institute of Horticulture of the NAAS of Ukraine was approximately 15-25 years old and rated at 4-5 points. The condition of *C. canadensis* L. and *C. siliquastrum* 'Alba' growing on the

territory of O.V. Fomin Botanical Garden is rated as “good” – there is a small number of dry branches and the trees are about 40-45 years

old and 20 years old, respectively (Fig. 2). Detailed evaluation information for each tree is provided in Table 1.



Figure 2. General view of plantings of *Cercis canadensis* L.

Note: a – group of plants near the Beresteyska metro station; b – a plant on Tabirna Street; c – group of plants on Kirponos Street; d – cauliflory phenomenon

Source: photo by the authors

Table 1. Condition and location coordinates of the plants under study

No.	Coordinates	Code	Plant condition assessment	Location	Type of plantings
1	50.3831696 30.5027045	S1	4	O.V. Fomin Botanical Garden*	Single planting
2	50.3831696 30.5027045	S7	4	O.V. Fomin Botanical Garden	Group
3	50.351953 30.442145	S8	5	Institute of Horticulture of NAASU	Single planting
4	50.459376, 30.419858	S9	3	Beresteyska metro station	Group
5		S2	4		
6		S10	4		
7		S3	4		
8		S4	4		
9		S5	4		
10		S11	2		
11	50.459444	S13	3	Tabirna Street	Single planting
12	30.421137	S14	3	Tabirna Street	Single planting
13	50.3831696 30.5027045	S15	5	Kirponos Street	Group
14		S12	3		
15		S6	4		

Note: **Cercis siliquastrum* ‘Alba’; NAASU – National Academy of Agrarian Sciences of Ukraine

Source: compiled by the authors

The dynamics of shoot development and growth during the growing season is quite accurately described by the Gaussian function, which under ideal conditions is bell-shaped with a peak in the centre or close to it:

$$f = a \cdot \exp\left(-0,5 \cdot \left(\frac{x-x^0}{b}\right)^2\right). \quad (1)$$

As can be seen from the regression models below (Fig. 3), the peaks of the curves are shifted

to the right, which may indicate that the plants do not have enough sum of active temperatures to complete the processes of lignification of shoots and a full transition to winter. In addition,

during the observation of plants during the growing season, it was found that *Cercis canadensis* L. is characterised by the separation and falling of one or more of the last internodes.

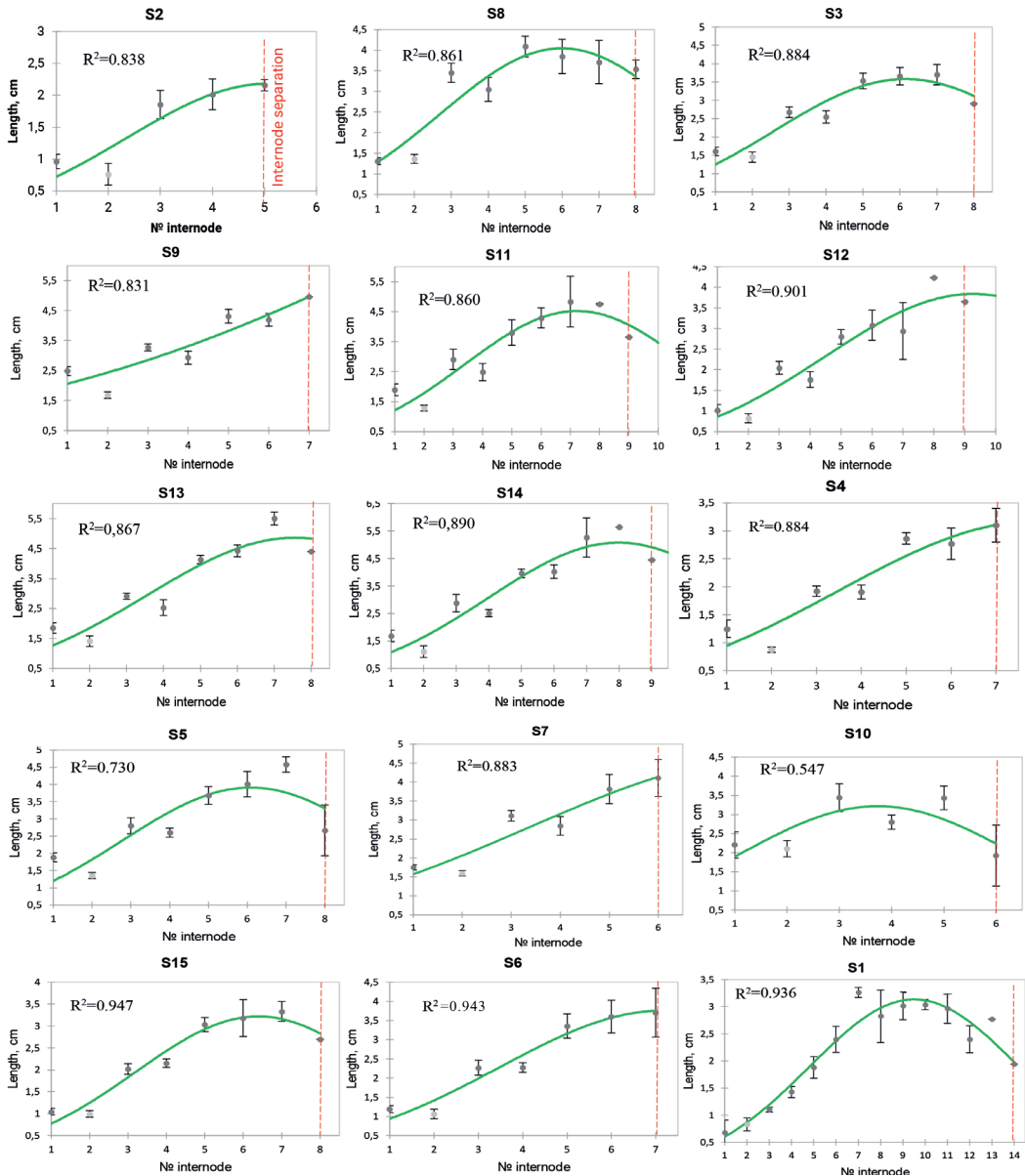


Figure 3. Dynamics of changes in the length of internodes of annual shoots during the growing season

Source: developed based on the authors' research

A decrease in the approximation coefficients of the Gaussian model describing the dynamics of changes in the length of internodes is associated with a shift of the maximum growth

peak to the right in the time coordinate. Indicators of the length and diameter of internodes of annual shoots and their ratio, depending on the place of plant growth, are shown in Table 2.

Table 2. Morphometric parameters of plants *Cercis* L. ($\bar{x} \pm SE$, $n=5$)

Location and code	Number of internodes, units	Internode length (l), cm			Diameter (d), cm			l/d			Total length, cm
		1	3	5	1	3	5	1	3	5	
A ₁ (S2)	4.8	0.96 ±0.11	1.86 ±0.22	2.16 ±0.09	0.21 ±0.005	0.18 ±0.008	0.14 ±0.011	4.57 ±0.48	10.13 ±0.96	15.28 ±0.72	7.32
A ₂ (S9)	5.8	2.48 ±0.14	2.93 ±0.22	4.96 ±0	0.25 ±0.022	0.20 ±0.014	0.17 ±0.0	10.21 ±0.38	14.84 ±0.67	29.18 ±0.0	18.20
A ₃ (S10)	5.6	2.20 ±0.34	2.80 ±0.19	1.92 ±0.79	0.21 ±0.011	0.17 ±0.009	0.12 ±0.011	10.35 ±1.39	16.22 ±0.31	26.96 ±1.66	15.90
A ₄ (S3)	5	1.61 ±0.12	3.53 ±0.21	2.91 ±0.0	0.28 ±0.029	0.20 ±0.022	0.15 ±0.0	5.96 ±0.76	18.46 ±2.07	19.40 ±0.0	19.01
A ₅ (S4)	6.2	1.25 ±0.16	1.91 ±0.12	3.10 ±0.3	0.24 ±0.018	0.19 ±0.016	0.13 ±0.01	5.33 ±0.78	10.30 ±1.02	23.81 ±0.48	12.28
A ₆ (S5)	7.2	1.88 ±0.13	3.68 ±0.26	2.67 ±0.74	0.28 ±0.018	0.21 ±0.02	0.14 ±0.01	6.73 ±0.43	17.70 ±1.34	18.52 ±3.69	20.79
A ₇ (S11)	7	1.89 ±0.2	3.80 ±0.42	3.65 ±0.0	0.26 ±0.025	0.19 ±0.028	0.15 ±0.0	7.35 ±0.74	20.40 ±1.66	24.33 ±0.0	21.33
B ₈ (S13)	6.6	1.85 ±0.18	4.13 ±0.14	4.40 ±0.0	0.26 ±0.016	0.19 ±0.018	0.12 ±0.0	7.36 ±0.98	23.06 ±2.95	36.67 ±0.0	20.54
B ₉ (S14)	6.8	1.68 ±0.21	3.96 ±0.15	4.45 ±0.0	0.26 ±0.031	0.20 ±0.031	0.18 ±0.0	6.40 ±0.19	21.32 ±2.66	24.72 ±0.0	20.53
C ₁ (S15)	7	1.05 ±0.08	3.03 ±0.16	2.70 ±0.0	0.28 ±0.009	0.21 ±0.013	0.15 ±0.0	3.70 ±0.2	14.96 ±1.14	18.00 ±0.0	15.64
C ₂ (S12)	6.8	1.02 ±0.14	2.80 ±0.17	3.65 ±0.0	0.24 ±0.029	0.19 ±0.029	0.17 ±0.0	4.71 ±0.91	16.38 ±2.13	21.47 ±0.0	14.25
C ₃ (S6)	6.2	1.19 ±0.09	2.28 ±0.13	3.71 ±0.64	0.26 ±0.026	0.22 ±0.023	0.17 ±0.005	4.71 ±0.55	10.88 ±1.14	22.59 ±4.53	14.53
D(S8)	7	1.31 ±0.08	4.09 ±0.25	3.54 ±0.23	0.26 ±0.019	0.19 ±0.018	0.14 ±0.015	5.13 ±0.45	21.85 ±1.14	26.33 ±1.26	20.74
E ₁ (S1)	10.2	0.68 ±0.23	2.83 ±0.48	1.94 ±0.0	0.42 ±0.033	0.28 ±0.029	0.22 ±0.0	1.58 ±1.07	9.96 ±1.46	8.82 ±0.0	20.51
E ₂ (S7)	5.4	1.75 ±0.07	2.85 ±0.25	4.11 ±0.49	0.30 ±0.024	0.26 ±0.026	0.23 ±0.003	5.96 ±0.66	11.19 ±0.75	17.61 ±2.13	14.82

Note: A – Beresteyska metro station; B – Tabirna Street; C – Kirponos Square, D – Institute of Horticulture of NAAS of Ukraine; E - O.V. Fomin Botanical Garden (E1 – *Cercis siliquastrum* ‘Alba’; E2 – *Cercis canadensis* L.); where “1”, “3”, “5” – first, middle, and last internodes

Source: compiled by the authors

Table 2 shows an inverse relationship between the length of the internode and its diameter. For plants growing in conditions of shading or high humidity, this ratio increases, which is generally typical for plants that usually grow

in lighted areas. It was also found that in *Cercis* L. plants, probably due to the insufficient amount of the sum of active temperatures, the process of development of a separate cell layer begins, which blocks the transport system and

the supply of nutrients to the top of the shoot (Fig. 4). This process was more active in plants in sunny areas, possibly due to the more intensive growth of annual shoots.



Figure 4. Process of separation of the last internodes on the tops of shoots of *Cercis canadensis* L.

Note: a – upper internode separation zone

Source: developed by the author

In the places of “scarring”, and living parts of the internode and those that began to die, the development of a layer of cells similar to the periderm was observed. The overgrown periderm thickens in the area of the conductive bundles, which leads to a blockage of nutrient

supply to the shoot apex. As a consequence of this process, the last internodes die off. Hypothetically, this process is genetically determined and is aimed at protecting the apical meristem during the dormant period of plants in winter (Fig. 5).

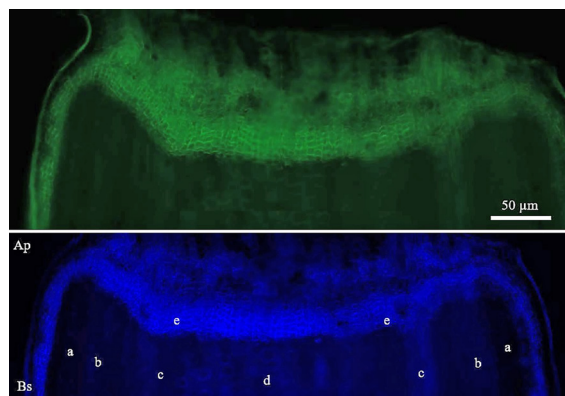


Figure 5. Autofluorescence of annual shoot node tissues in the zone of separating layer formation (radial section)

Note: a – cortex; b – phloem; c – xylem; d – core parenchyma; e – separation layer; Ap – apical part; Bs – basal part; DAPI ($\lambda_{exc}=357/44$ nm; $\lambda_{em}=447/60$ nm); GFP ($\lambda_{exc}=482/25$ nm; $\lambda_{em}=524/24$ nm)

Source: developed based on the authors’ research

Biochemical profiling of secondary metabolites of periderm and bark of annual plant shoots of *Cercis canadensis* L. identified 15 substances that, according to Rf indicators and the specifics of autofluorescence in ultraviolet (UV) ($\lambda=365$ Nm), belong to phenol carboxylic acids, their conjugants and flavonoids. Based on the results of cluster analysis, according to the characteristics of phytochemical profiles, 3 main groups of plants were identified. For plants that have developed the first cluster, it is characteristic that they grow in sunny areas without signs of shading, but there are no substances with Rf-0.69 and Rf-0.77. Plants that are combined according to the biochemical profile in the

second cluster are characterised by the presence of flavonoids with Rf-0.69 and Rf-0.77. Externally, these plants have no signs of growth suppression, without much damage to the trunk or tree as a whole. 3 out of 5 plants grow in a group planting, other plants also grow in a sunny area, and their age is in the range of 25-35 years. In addition, the plant under the code S5 is characterised by a fairly high concentration of the substance Rf-0.69 and Rf-0.77. This plant developed chlorophyll-deficient leaves during the growing season. There may be a certain relationship between the increased concentration of substances and depigmentation of the leaf plate, which requires additional research (Fig. 6).

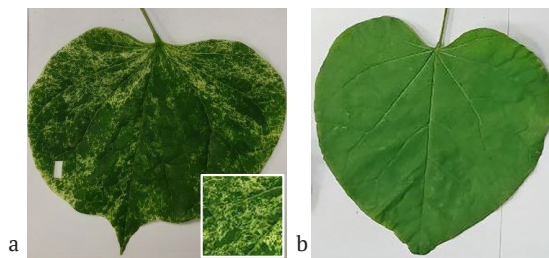


Figure 6. Chlorophyll-deficient (a) and normal (b) leaf

Source: developed by the authors

The third cluster was divided into 2 sub-clusters. In one of them, a substance with an Rf of- 0.39 was found, which was not present in any sample of the bark and periderm of

annual shoots. A reduced amount of phenolic compounds on the chromatogram is typical for plants that are united in the second subcluster of the third cluster.

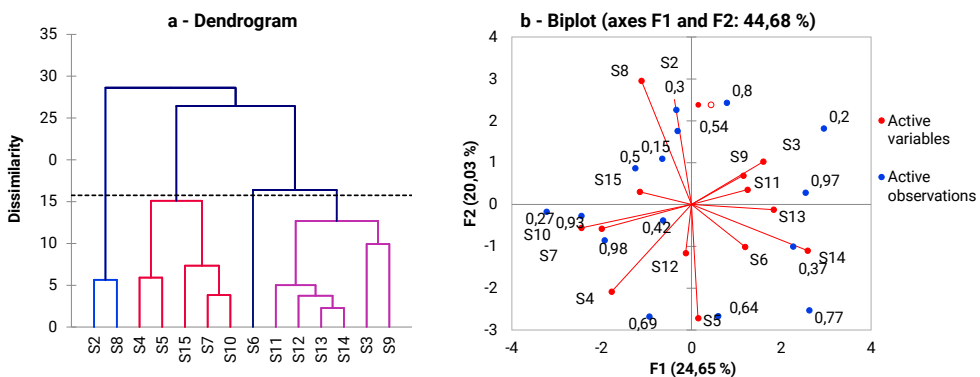


Figure 7. Results of cluster (AHC) (a) and biplot principal component analysis (PCA) (b)

Source: developed by the authors

These plants grow in shaded conditions and in drafts. Given a direct relationship between the lighting mode and the synthesis of phenols, phenolic compounds play an important role in protecting plants from ultraviolet radiation. And the synthesis centres of some of these substances are partially connected with chloroplasts. This explains the reduced concentration of substances in the periderm and bark of plants of this subclasser.

Based on the results of biplot analysis based on principal components (PCA), it was found that the total variance for the main components F1 and F2 is 44.68% (Fig. 7). According to the first main component, substances with a significant contribution to the total dispersion of Rf-0.97; 0.37 and Rf- 0.93; 0.27 are distinguished.

Discussion

According to X.-C. Li *et al.* (2021), the centre of origin and further distribution of the genus *Cercis* L. are sub-tropical climate zones and southern warm temperate climates in Asia, southern Europe, and the southwestern United States. And the Paleogene fossils from Eurasia and North America indicate a long history of the genus. *Cercis* L. in the middle and low latitudes of the Northern Hemisphere. The modern natural range of the genus is part of the Holarctic realm, some areas of which are separated by The Atlantic and Pacific oceans, but as noted by L. Koldar *et al.* (2001), the similarity of species growing in North America and Southern Europe is explained by the fact that the flora of these territories has common features, which are due to the fact of the existence of Laurasia – the continent that united North America and Eurasia. In particular, this is the basis for the study by C. Davis *et al.* (2002), arguing that *Cercis canadensis* L. from the eastern part of North America is more closely related to *Cercis siliquastrum* L., which grows in the western part of Europe. The similarity of plants within the

same genus is often confirmed by biochemical studies. This is due to the fact that the synthesis of secondary metabolites plays an important role in adaptation processes. The author of this study found similarities in the phenolic profiles of plants that grew in different parts of Kyiv. It is assumed that the similarity of phytochemical profiles is due not only to growing conditions and environmental factors, but also to genetic similarity. In addition to this, it is revealed that the process of separation of the last internodes is inherent not only for *Cercis canadensis*, but also for *Cercis siliquastrum* 'Alba'.

Flavonoids have a direct or indirect effect on plant nutrition and growth (Likhanov *et al.*, 2023). According to S. Hassan *et al.* (2012), flavonoids, depending on their structure, cause positive chemotaxis of rhizobia, are able to suppress root pathogens, chelate soil nutrients, etc. Under the conditions of pathological processes with the development of lifetime wood defects, the composition of flavonoids changes (Likhanov *et al.*, 2019). In particular, it was found that plants that grew under stressful conditions (shading, drafts, soil salinisation, etc.) had less saturated phytochemical profiles. During the studies, it was found that plants that grew in sunny areas have flavonoids with Rf-0.69 and Rf-0.77. According to A. Samanta *et al.* (2011), flavonoids protect plants from various biotic and abiotic stresses and can act as a unique UV filter, function as signalling molecules, allelopathic or antimicrobial protective compounds. In particular, as noted by A. Rehman *et al.* (2023), plant heat resistance depends on a complex interaction of various factors, including activation of heat stress responses, signalling pathways, and plant hormone biosynthesis. This intricate network of mechanisms leads to the production of several secondary metabolites that play a crucial role in improving plants' ability to cope with high temperature stress. E. Koç *et al.* (2023) indicate

that an increase in the content of secondary metabolites in the plant may indicate a close relationship between secondary metabolites and tolerance to biotic and abiotic factors. J. Al-Khayri *et al.* (2023) confirm that due to the action of secondary metabolites, plants can synthesise natural insecticides-repellents. Given that secondary metabolites perform a variety of functions, including mediating interactions between organisms, responding to environmental factors, and protecting plants from infections, pests, and herbivores. Similarly, plant microbiomes are directly or indirectly involved in many of the above processes, controlling plant metabolism. In particular, J. Herlina *et al.* (2022) concluded that plants can influence their microbiome by releasing various compounds, and also found that the microbiome can influence the host plant's metabolome. In addition to the protective function, flavonoids can be considered as unique indicators of plant condition, with the determination of growing conditions. According to the study by A. Salatino *et al.* (2000), the presence of kaempferol glycosides is characteristic of taxa *Cercis* L. from sufficiently moistened regions, while plants from arid growing conditions do not have them. According to E. Ewais (1997), various plant species are resistant to excessive heavy metal content in the soil. The researcher suggests that an integral indicator of the toxic effect of metals on plants is the inhibition of their growth and a decrease in vegetative mass. In addition, plants growing near roadways are exposed to increased negative effects of urban environmental factors. In these studies, *Cercis canadensis* trees growing directly near the roadway had a more depressed state than other specimens in group plantings. In the phytochemical profile of this plant, a substance (Rf-0.39) was found, the presence of which can be a marker of plant stress on the action of negative factors.

At the same time, under the conditions of optimising the care of plants, carrying out additional measures, creating lawns, they can improve the ecological state of the urban environment, in particular, reduce the temperature and increase humidity, retain small dust particles, etc. As noted by V. Shlapak (2006), plants of the genus *Cercis* L., although require optimal humidity, they are better able to tolerate a lack of moisture than an overabundance of it, since, according to the researcher, when the soil moisture is 80%, plant development is suppressed, which eventually leads to death. Plants growing in urban environments suffer not only from insufficient amounts of micro- and macronutrients, but also from the negative effects of heavy metals, which accumulate due to their absorption through the root system or leaves. Different plant species are resistant to excessive heavy metal content in the soil. An integral indicator of the toxic effect of metals on plants is the suppression of their growth and a decrease in vegetative mass.

L. Koldar *et al.* (2022) give an example that due to the dense crown and rather large leaf blade, plants of this genus can retain small particles of dust and heavy metals. According to L. Hakimi *et al.* (2015), *Cercis* L. can be an indicator of the presence of heavy metals in the soil, in particular cadmium, due to the plant's ability to accumulate it in the leaves. Based on the research data, it can be assumed that due to the high drought resistance, dense crown, and large leaves of the plant of the genus *Cercis* L., they are able to create large shady spaces, which will increase the level of comfort for urban residents.

Conclusions

A number of patterns were observed. In particular, when measuring the length and diameter, it was found that in plants that grew in shaded areas, the last internodes had signs of freezing. As a result of the conducted studies, the inverse

relationship between the diameter of internodes and their length was established. During the observation, the effect of total death of the last internodes at the top of annual shoots was revealed. Phenolic profiles of experimental plants showed that the accumulation of secondary metabolites depends on environmental conditions, humidity, and the level of solar insolation. It was also experimentally confirmed that plants within the genus can be distinguished based on the variability of phenolic profiles.

Plants of the genus *Cercis* L. have fully adapted to the climatic and urban conditions of growth. It is possible that this is facilitated by the phenomenon of death of one or more upper internodes, as an adaptation to possible freezing of the ends of shoots. Based on anatomical and histological studies, it was found that in the shoots, at the points of separation, the conductive bundles are blocked due to the development of the periderm. Because of this, the supply of nutrients to the last 2-3 internodes stops. It is established that the profiles of phenolic compounds that accumulate in the periderm directly depend on the place of growth and the general condition of the plant, in particular, the accumulation of phenolic compounds occurs more intensively in plants growing in sunny areas. The relationship between the growth of shoots and the accumulation of secondary metabolites in them, as a reaction to plant growth conditions, is also given.

Lower saturation of phytochemical profiles and concentrations of individual compounds is

characteristic of young plants and those with signs of suppressed growth in shaded areas. Plants of the genus *Cercis* L. require a high level of insolation. Perhaps this is due to the fact that the natural range of the genus is formed in territories with a Mediterranean and mild Atlantic climate. Thus, when landscaping urban areas, it is critical for plants of this genus to select habitat conditions that correspond to the plants' needs for high levels of insolation and sensitivity to drafts. In general, these species are resistant to air and soil pollution by heavy metals and can be recommended for urban landscaping.

Further research could include analysis of the variability of responses to different types of pollution in the urban environment and consideration of interactions between different elements of the urban landscape and plants. Understanding these aspects can help develop effective urban green space management strategies aimed at preserving biodiversity and improving the quality of the urban environment.

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Conflict of Interest

None.

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Вплив факторів міського середовища на морфометричні показники та накопичення вторинних метаболітів у пагонах *Cercis canadensis* L. та *Cercis siliquastrum* 'Alba'

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Анотація. Врахування ролі зелених насаджень у міському озелененні надзвичайно актуальне, оскільки вони не лише прикрашають міський ландшафт, а й ефективно зменшують забруднення повітря, регулюють мікроклімат та відіграють важливу роль у покращенні екології та якості життя мешканців. Метою дослідження було встановлення впливу чинників міського середовища на розвиток і вторинний метаболізм рослин роду *Cercis* L. Для досліджень було обрано рослини, які зростають у місті Київ (Україна) в умовах різної вологості повітря, антропогенним навантаженням, надлишком або нестачею інсоляції. Процеси росту рослин вивчали за морфометричними показниками однорічних пагонів *Cercis siliquastrum* 'Alba' та *Cercis canadensis* L., що зростають за різних умов. У дослідженнях використовували методи морфометрії, флуоресцентної мікроскопії, високоефективної тонкошарової хроматографії

та методи регресійного аналізу. Дані досліджень свідчать, що недостатня кількість сонячного світла негативно впливає на ріст пагонів. Встановлена специфічність фенольних профілів за якими можна розрізняти види *Cercis canadensis* L. та *Cercis siliquastrum* 'Alba'. Аналіз головних компонент підтвердив, що фенольні профілі залежать від умов місцезростання та впливають на ріст і розвиток рослин. Для аналізу динаміки росту однорічних пагонів протягом вегетації використовували модель Гауса, яка дозволила доволі точно описати специфіку формування міжвузлів протягом вегетаційного періода. Ця модель дозволила виявити феномен відпаду останніх міжвузлів наприкінці вегетації, через що спостерігалось відхилення морфометричних показників метамерів від нормального розподілу по осі часу. Анатомічні дослідження підтвердили, що відділення одного або декількох останніх міжвузлів відбувалось через активне корковіння внутрішніх тканин стебла, блокування роботи ксилеми і формування віддільного шару, що призводило до відпадання верхівки пагона. Описаний феномен має ознаки адаптації рослини до низьких температур у зимовий період. Верхівки пагонів часто не встигають здерев'яніти і накопичити необхідну кількість кріопротекторів. За умов формування віддільного шару доступні енергетичні ресурси перерозподіляються в бічні бруньки, які отримують необхідні ресурси для підготовки до зимового періоду і забезпечують новий приріст у наступний вегетаційний період. Адаптивний потенціал досліджених видів роду *Cercis* L. підтверджує перспективність їх використання в озелененні міських екосистем, що може позитивно вплинути на збереження біорізноманіття в цілому

Ключові слова: юдине дерево; екологічні чинники; зелені насадження; флавоноїди; адаптація

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Recovery of Velykyi Luh through ecological restoration of the Kakhovka Reservoir

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Abstract. The relevance of modern environmental issues requires comprehensive approaches to the restoration and preservation of natural ecosystems, specifically through ecological restoration as a tool to eliminate the effects of anthropogenic interventions. The purpose of this study was to survey the territory of the Kakhovka Reservoir using remote sensing and to propose a way to restore the historical territory of the Kakhovka Reservoir of Velykyi Luh. The following research methods were employed: empirical, analysis and systematisation, remote sensing, geographic information systems. The study consisted of two main stages. The first stage included an analysis of the dynamics of the historical territory of Velyky Luh, from the end of the 19th century to the present day. The second stage involved comparing the dynamics of the area's restoration using 19th-century mapping data and 21st-century satellite imagery. The use of modern technologies, including the analysis of satellite images of the degraded area and three indices of the EO Browser software, such as the differential vegetation index, the normalised differential humidity index, and the differential water index, helped to obtain data on the state of vegetation and water resources in the study area. The analysis of the patterns between these indicators made it possible to determine the close interaction between plant growth rates and their moisture availability. The biomass growth on the territory of the Kakhovka Reservoir was measured from the moment of dewatering to

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November 2023. The results obtained indicate that it is possible to effectively restore the ecosystem of the Velykyi Luh through ecological restoration. This process involves the selection of optimal biotopes for the restoration of the historic area, which is a crucial step in conserving biodiversity and stabilising the natural environment in the Kakhovka Reservoir. The findings of the study on a new approach to ecological restoration based on high-precision technologies and in-depth analysis of ecosystem dynamics will contribute to the development of scientific approaches to the restoration of natural landscapes and will be an important contribution to modern environmental practice

Keywords: remote sensing of land; vegetation; ecology; regeneration; historical area

Introduction

In the light of current environmental challenges, addressing the loss and degradation of natural ecosystems requires the implementation of comprehensive measures, including the active use of ecological restoration. The key purpose of this aspect is to restore ecosystems affected by anthropogenic interventions and identify opportunities to use restoration as a means of eliminating the effects of human activity that adversely affects the natural environment.

It is possible to obtain information about any object or process without direct contact with them using remote sensing (RS). According to S.O. Dovhyi *et al.* (2019), remote sensing is a thematic analysis of both natural and artificially generated radiation of the earth's surface in the ultraviolet to radio wave ranges. The development of geodetic and cartographic knowledge has made it possible to link a satellite image to a concrete location on the earth's surface that it represents. S.A. Shevchuk (2022) showed that monitoring remote sensing data allows identifying hydraulic, water management, and water objects that have been damaged or subjected to negative anthropogenic impacts during hostilities. The tasks set are not trivial, but the use of modern remote sensing and geographic information technologies (GIT) helps to systematically obtain and interpret data on photometric parameters of individual water bodies and catchment areas in a wide spectral

range with the necessary resolution and frequency of information updating, and to assess their sanitary and biological characteristics. C.B. Pande *et al.* (2024) considered that remote sensing provides opportunities for obtaining valuable information about various objects, enabling monitoring of the surface and the dynamics of ongoing processes, and is widely used around the world. In India, remote sensing is used to assess the soil cover in winter and to detect changes in the impact on evapotranspiration parameters. In the United States, remote sensing is used to assess high-resolution forest cover in an ecologically diverse landscape (Zurqani, 2024). Flood mapping in Pakistan is carried out using remote sensing and geographic information systems (GIS) (Ghouri *et al.*, 2023). In the Kashmir Himalayas, the dynamics of wetlands are being assessed based on satellite Earth observation data (Alam *et al.*, 2023). The use of remote sensing is associated not only with uninhabited areas, but also with inhabited ones, as it is also used to map and monitor cities (Kumar *et al.*, 2023).

Ecological restoration is key to counteracting anthropogenic biodiversity degradation and reducing disaster risk. However, there is limited knowledge of the barriers that prevent wider adoption of restoration practices, despite the high-level political priority to halt biodiversity loss. Ecologists are looking for opportunities

to turn restoration projects into long-term hypothesis-driven ecological restoration experiments, and for funding, time, and institutional support to do so. R.E. Young *et al.* (2023) identified eight principles for ecological restoration: involving stakeholders; applying different types of knowledge; obtaining information from relevant reference ecosystems, considering environmental changes; sustaining ecosystem restoration processes; evaluating against clear goals and objectives using measurable indicators; aiming for the highest degree of restoration; obtaining cumulative value when applied at large scales; and application of continuous restoration activities. The environment that has been restored after considerable human impacts on the river environment may have a higher or lower ecological value compared to the original state. However, in the context of an anthropocentric assessment, such restored environments are certainly much more valuable today than they were before the restoration programme. Ecological restoration is used to restore areas around the world. In China, W. Hong *et al.* (2024) used indices of damage to the green space ecosystem and its ability to recover to build a discrimination matrix for an ecological recovery model under 12 different scenarios. T. Alamenciak *et al.* (2023) described that forest, peatland, grassland, and lake ecosystems are being restored through ecological restoration in Canada. The practice of ecological restoration, as a deliberate activity that initiates or accelerates the restoration of an ecosystem (which has been degraded, damaged, or destroyed), factoring in its integrity and stability, includes a wide range of projects. These include erosion control, reforestation using local plant genetic resources, removal of introduced species and weeds, revegetation, reclamation of disturbed lands, river revitalisation, reintroduction of native species, and improvement of habitat and habitat quality for target species (Restoration Ecology,

n.d.). The territory can be restored using various methods, including ecological restoration, reclamation, and bioremediation. P. Li *et al.* (2022) note that technologies related to ecological river restoration are essential for improving river habitat and biodiversity, as well as for restoring river ecosystem functions. Revegetation is used to artificially restore soil fertility and vegetation cover after anthropogenic disturbance of nature. The treatment of water, soil, and atmosphere using the metabolic potential of biological objects (plants, fungi, insects, worms, bacteria) or their enzymes is possible using a set of methods referred to as bioremediation.

The purpose of this study was to investigate the territory of the Kakhovka Reservoir using remote sensing and to propose a method of restoring the Velykyi Luh on the territory of the Kakhovka Reservoir.

Objectives: to study the territory of the Velykyi Luh in the historical aspect; to analyse the dewatered territory of the Kakhovka Reservoir using remote sensing; to investigate and compare the territory of the Kakhovka Reservoir during the 19th-21st centuries in the EO Browser software using the normalised differential water index, normalised differential vegetation index, normalised differential humidity index; based on the analysis, to propose optimal biotopes for the restoration of the historical territory by means of ecological restoration.

Materials and Methods

The study of the historic territory of Velykyi Luh was carried out in two stages between June and December 2023. The first stage analysed the territory of the Velykyi Luh from the end of the 19th century to 2024 on the territory of the Kakhovka Reservoir from a historical perspective. The second stage was a comparison of the dynamics of the restoration of the Velykyi Luh area using a map and 21st-century satellite images. Access was gained to the state of the

vegetation on the territory of the Velykyi Luh of the Kakhovka Reservoir. To determine the relationship between plant growth rates and their moisture availability, the regularity between the normalised differential vegetation index (NDVI) and the normalised differential moisture index (NDMI) in the territory of the Velykyi Luh was analysed. The normalised differential water index (NDWI) (1) was used to analyse the dynamics of the water surface from 1990 to

2010. The normalised differential water index is the most appropriate index for mapping water bodies. Water bodies have a value greater than 0.5. Vegetation is characterised by lower values. Artificial objects have positive values from 0 to 0.2 (NDWI..., n.d.).

$$NDWI = \frac{B03 - B08}{B03 + B08}, \quad (1)$$

where *B03* – Band 3 – Green – 560 nm; *B08* – Band 8 – Near infrared (NIR) – 842 nm (Table 1).

Table 1. Specification of spectral bands for the Sentinel-2 satellite

Band	Central wavelength, nm
1	443
2	490
3	560
4	665
5	705
6	740
7	783
8	842
9	865
10	1380
11	1610
12	2190

EO Browser software with access to Sentinel-2 and Landsat 4-5 TM satellites was used to determine NDVI, NDMI, and NDWI. Archival images and data from 2020-2023 were analysed. Satellite images were selected with 0% cloud coverage. The authors received and analysed 6 data each from the NDVI and NDMI indices. EO Browser software was used for digital map processing. NDVI was calculated using formula (2) and can range from -1 to 1, where negative values indicate water:

$$NDVI = \frac{B08 - B04}{B08 + B04}, \quad (2)$$

where *B08* – Band 8 – Near-infrared (NIR) – 842 nm; *B04* – Band 4 – Red – 665 nm (Table 1).

The range of NDVI values is from -1 to 1. Negative NDVI values (values approaching -1) indicate approaching water. Values close to zero (from -0.1 to 0.1) indicate a location on exposed rocks, sand, or snow. Low positive values are typical for shrubs and grasslands (approximately 0.2-0.4), while high values are typical for temperate forest vegetation (values close to 1). The index was calculated according to the emission or reflection from the red channel of about 0.66 μm and the near-infrared channel of about 0.86 μm (Gao, 1996).

NDMI is a normalised difference moisture index with near-infrared (NIR) and short-wave infrared (SWIR) bands for displaying moisture. NDMI was used to monitor changes in

leaf water content. The SWIR bands depend on changes in the water content of the vegetation and the structure of the spongy mesophyll of the plant canopy. The water content does not affect the NIR but depends on the internal structure of the leaves and the dry matter content of the leaves. The NDMI was calculated and is found according to the formula (3) and can vary from -1 to 1. Negative values may indicate a water stress.

$$\text{NDMI} = \frac{B08 - B11}{B08 + B11}, \quad (3)$$

where *B08* – Band 8 – Near-infrared (NIR) – 842 nm; *B11* – Band 11 – Shortwave Infrared (SWIR) – 1610 nm (Table 1).

The normalised differential moisture index (NDMI) is used to determine the moisture content of vegetation and monitor drought (NDMI..., n.d.). The range of NDMI values is from -1 to 1. Negative NDMI values (values close to -1) correspond to open ground. Values close to zero (-0.2-0.4) indicate water stress.

High positive values correspond to a high vegetation cover that is not under water stress (approximately 0.4-1). Based on the data obtained, biotopes were selected for the ecological restoration of the historical area of Velykyi Luh on the territory of the Kakhovka Reservoir. The study was conducted following the Convention on the Trade in Endangered Species of Wild Fauna and Flora (1973) and the Convention on Biological Diversity (1992).

Results and Discussion

Velykyi Luh is the historical name of the area, a giant river floodplain (over 400 km²) that existed on the left bank of the Dnipro River, between the Dnipro and the left tributary of the Konka River and stretched in a wide strip along the right bank from the mouth of the Serednia Khortytsia River. The entire area belonged to the Zaporizhzhian Sich and is therefore a crucial historical monument of the Ukraine (Fig. 1) (Solodko *et al.*, 2024).

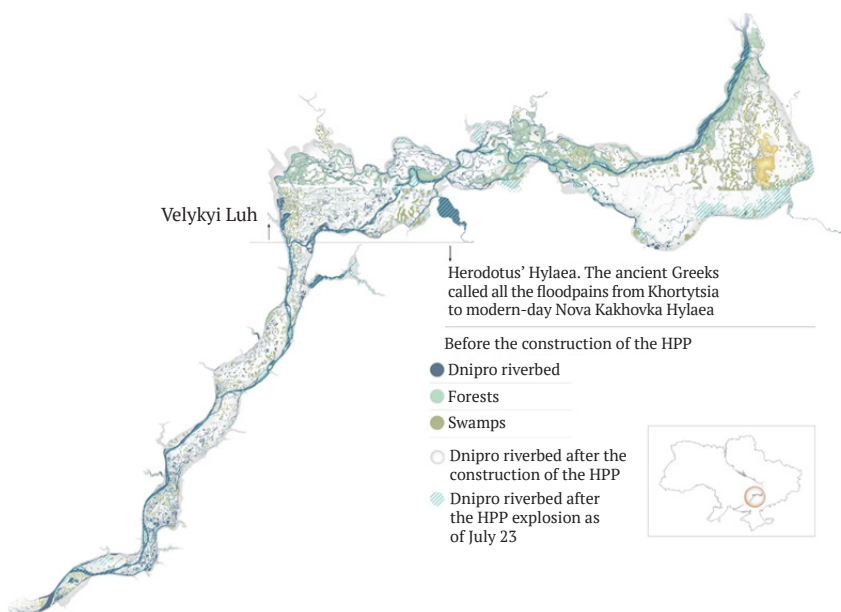


Figure 1. Velykyi Luh

Source: P. Solodko *et al.* (2024)

Velykyi Luh was flooded by the waters of the Kakhovka Reservoir (Fig. 2a) in 1955-1957, except for some areas. The reservoir was 230 km long and had an average width of 9.4 km (maximum width of 24 km). The area was 2,155 km² and the volume of water was 18.2 km³. The coastline was 896 km long. As a result of the reservoir creation, about 90 villages and the historical monument of Ukraine, Velykyi Luh, where rare plants grew, were flooded (Fig. 2b). Even after the flooding of the Velykyi Luh, unique vegetation was preserved among the remains of the floodplains,

including relict, endemic, and rare plant groups: *Salvinia natans* L., *Trapa natans* L., *Nymphoides peltata* (S.G. Gmel.) O. Kuntze), *Aldrovanda vesiculosa* L., *Nymphaea alba* L., *Nuphar lutea* L., *Sagittaria sagittifolia* L., *Glyceria arundinacea* Kunth, *Ceratophyllum tanaiticum* Sapjegin and *Ceratophyllum submersum* L. On the islands and elevations of the left-bank sandy terrace (arena) of the Velykyi Luh, thickets of the endemic *Betula borysthena* Klovov have been preserved. These phytocoenosis are listed in the Green Book of the Ukraine (Velyky Luh..., 2023).

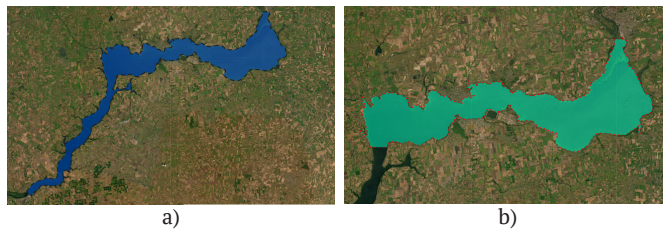


Figure 2. Satellite images of the Kakhovka Reservoir and Velykyi Luh

Note: a) territory of the Kakhovka reservoir; b) territory of the Velykyi Luh

Source: ArcGIS Online internet service and Maxar satellite

A comparable trend was observed in Australia in the second half of the 19th century, when thousands of dams were built, including 446 large dams (crest height >10 m). Flow regulation has altered the hydrology of major rivers and is recognised as a major cause of declining conditions in many Australian river and floodplain ecosystems (Arthington & Pusey, 2003). Prior to the flooding of the Velykyi Luh area, the floodplains were inundated with water from

early spring to early summer. In April, during the floods, the floodplains were almost a continuous expanse of water. The maximum water level occurred in late April and early May, and the minimum was in September and October (Petrochenko, 2009). Having investigated the dynamics of the water surface of the Kakhovka Reservoir from 1990 to 2010 using the normalised differential water index (NDWI), it was found that it stayed unchanged (Fig. 3).

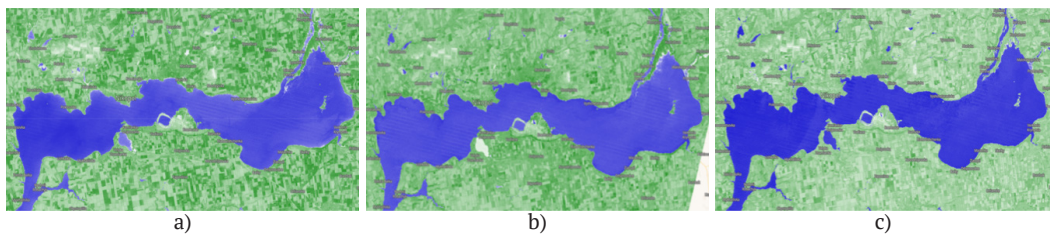


Figure 3. Satellite images of water surface dynamics from 1990 to 2010

Note: a) 1990; b) 2000; c) 2010

Source: EO Browser software, Landsat 4-5 TM L1 satellite, NDWI script

On 6 June 2023, as a result of the full-scale invasion, Russian troops blew up the dam of the Kakhovka hydroelectric power station, which

led to the reservoir being dewatering. The water rapidly began to recede, which led to the release of the Velykyi Luh to the surface (Fig. 4).

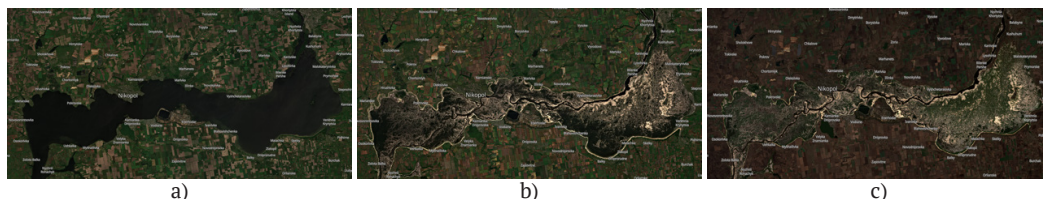


Figure 4. Dynamics of Kakhovka Reservoir dewatering and riverbed restoration (June-November 2023)

Note: a) 5 June; b) 20 June; c) 7 November

Source: EO Browser software, Sentinel-2 L2A satellite

The changes in the territory of the Velykyi Luh disturbed by anthropogenic impact, which arose as a result of the dewatering of the Kakhovka Reservoir, were analysed using the NDVI and NDMI indices in the EO Browser software. The normalised differential vegetation index (NDVI) is a simple but effective indicator for quantifying green biomass (NDVI..., n.d.). It is an indicator of vegetation health based on how plants reflect waves of light of a certain length.

Having analysed the satellite images of Figures 5a, 5b, 5c (NDVI) and Figures 5d, 5e, 5f

(NDMI) for 2020, a trend was found that as of 10 June, the vegetation condition was characterised by optimal indicators (NDVI within 0.6-1 and NDMI within 0.4-1) and did not indicate the presence of water stress (Fig. 5d). As of 5 July, this indicator was deteriorating (Fig. 5e), with NDVI ranging within 0.3-1 and NDMI – within -0.2-0.4.) On 28 October, the vegetation condition went from optimal to standard (NDVI within 0.2-1 and NDMI within -1-0.4), while the area around the Kakhovka Reservoir began to show signs of water stress (Fig. 5f).

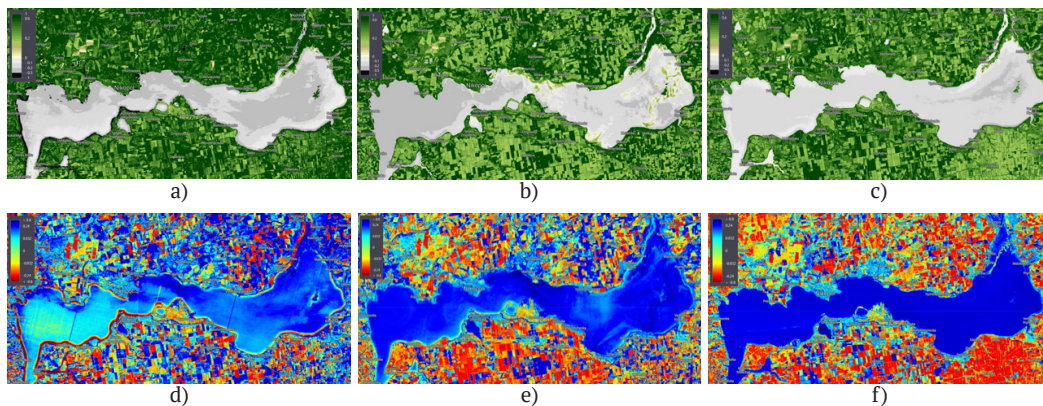


Figure 5. Quantification of green biomass and determination of the moisture content of vegetation in the Kakhovka Reservoir as of 2020.

Note: a) 2020-06-10 NDVI; b) 2020-07-05 NDVI; c) 2020-10-28 NDVI; d) 2020-06-10 NDMI; e) 2020-07-05 NDMI; f) 2020-10-28 NDMI

Source: EO Browser software, Sentinel-2 L2A satellite

Having analysed the satellite images in Figures 6a, 6b, 6c (NDVI) and Figures 6d, 6e, 6f (NDMI) for 2023 and compared them with analogous images of 2020 (Fig. 5a, 5b, 5c – NDVI and Fig. 5d, 5e, 5f – NDMI), the previously identified trend was recorded. There is also a difference in the 2023 indicators for June 5 (Fig. 6d, NDVI 0.8-1, NDMI 0.7-1) and November 7 (Fig. 6f, NDVI 0-0.5, NDMI -1--0.5) compared to the 2020 indicators for 10 June (Fig. 5d, NDVI 0.6-1, NDMI 0.4-1) and 28 October (Fig. 5f, NDVI 0.2-1, NDMI -1-0.4). As of 5 June 2023 (Fig. 6d, NDMI 0.7-1), the moisture content of vegetation was

significantly higher compared to 10 June 2020 (Fig. 5d, NDMI 0.4-1). However, by 7 November, the situation had changed dramatically (Fig. 6f, NDMI -1--0.5), and if by 19 August 2023 (Fig. 6e, NDVI 0.6-1, NDMI 0-0.4) the NDVI indicators were better compared to the relative humidity indicators by 5 July 2020 (Fig. 5e, NDVI 0.3-1, NDMI -0.2-0.4), the indicators for 7 November 2023 (Fig. 6f, NDVI 0-0.5, NDMI -1--0.5) were characterised by a small amount of biomass and critically lower moisture content in the vegetation around the Kakhovka Reservoir than on 28 October 2020 (Fig. 5f, NDVI 0.4-1, NDMI -1-0.4).

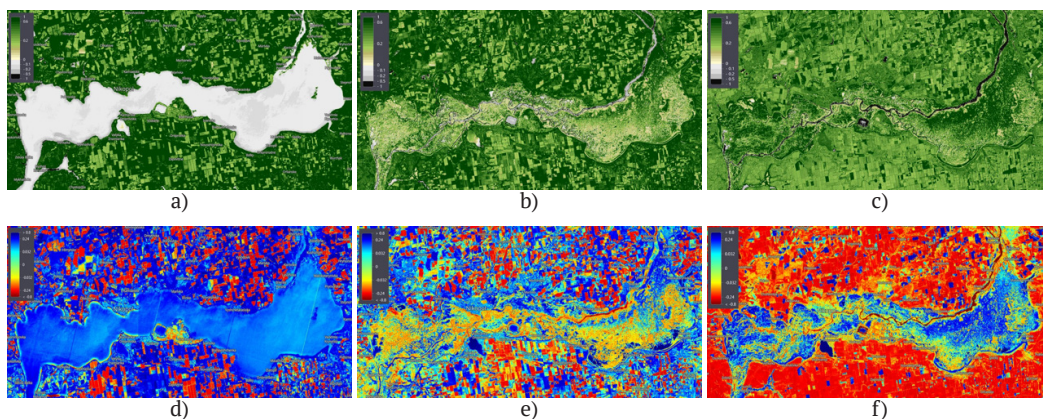


Figure 6. Quantification of green biomass and determination of the moisture content of vegetation on the territory of the Kakhovka Reservoir as of 2023

Note: a) 2023-06-05 NDVI; b) 2023-08-19 NDVI; c) 2023-11-07 NDVI; d) 2023-06-05 NDMI; e) 2023-08-19 NDMI; f) 2023-11-07 NDMI

Source: EO Browser software, Sentinel-2 L2A satellite

The method of ecological restoration is the most suitable for the restoration of historic areas. This method has a wide range of applications and is supported by accumulated experience in the environmental field. Ecological restoration should also factor in the spread of exotic plant species that can colonise a natural area. The spread of exotic populations can occur in the early stages of invasion in large natural areas that are not strictly monitored (D'Antonio & Meyerson, 2002). Invasive plants pose a consid-

erable threat to biodiversity, ecosystem management, agriculture and forestry, etc.

Based on the analysis conducted (Fig. 5-6), it was found that the Kakhovka Reservoir contributed to the relative stability of the water balance for vegetation. After the explosion of the Kakhovka Hydroelectric Power Plant, the gradual dehydration of the reservoir led to a stressful condition of the plants, which increased over the course of six months. However, there have also been positive changes, and

the water balance is now optimal as a result of natural vegetation regeneration. Thus, the vegetation that appears on the territory of the reservoir is not subject to water stress (NDMI approximately 0.4-1) and contributes to the formation of the necessary moisture. As a result, ecological restoration and biotopes restoration will contribute to the formation of the necessary water balance in this area. When carrying out ecological restoration, it is necessary to factor in the impact of exotic species that may complicate the restoration process.

At the same time, there may be circumstances where their removal may have unintended negative consequences or their use for restoration is desirable (D’Antonio & Meyerson, 2002). To achieve a sustainable outcome in restoring former coastal environments, a balance must be struck between ecological and human objectives (Chenoweth, 2006).

The area of the Velykyi Luh study area was measured (Fig. 7), which is 1,615.8 km², and the dynamics of biomass increase during August-November 2023 was calculated (Table 2).

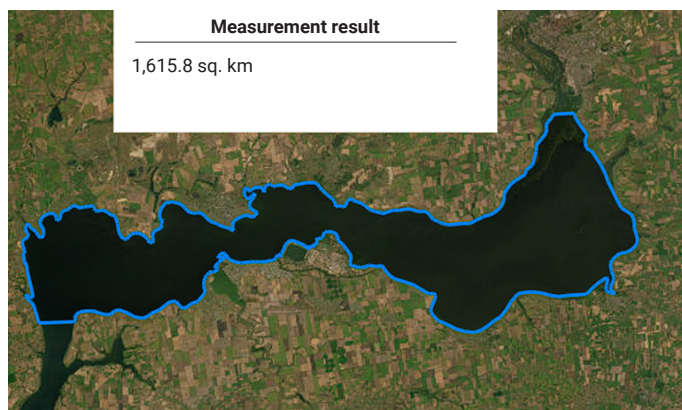


Figure 7. The area of the Velykyi Luh study area

Source: Arc GIS online service, Maxar satellite

Table 2. Biomass area and its increase on the territory of the Kakhovka Reservoir

Date	Biomass area, km ²	Increase in biomass area, km ²	Biomass area of the total area under study, %
19 August	≈311.48	–	19.27
8 September	≈570.22	258.74	35.29
7 November	≈737.61	167.39	45.65

Source: developed by the authors of this study

After the Kakhovka HPP was blown up and the territory of the Kakhovka Reservoir was drained, vegetation (biomass) was rapidly restored (Figs. 8a, 8b, 8c). From 19 August to 7 November 2023, the biomass area increased by 237% (Table 2). This shows the favourable conditions for further restoration of the

historical part of Velykyi Luh through ecological restoration. As of 25 November 2023, willow stands formed on the territory of the dewatered Kakhovka Reservoir (Belousova, 2023). This indicates the beginning of the formation of full-fledged floodplain willow and poplar stands, which were common in this

area before the 1950s when the reservoir was created. In general, the main woody plants that grew on the territory of the Velykyi Luh

are considered *Quercus* L., *Pyrus communis* L., *Salix* L., *Populus nigra* L., *Malus sylvestris* Mill. (Kashchenko, 1917).

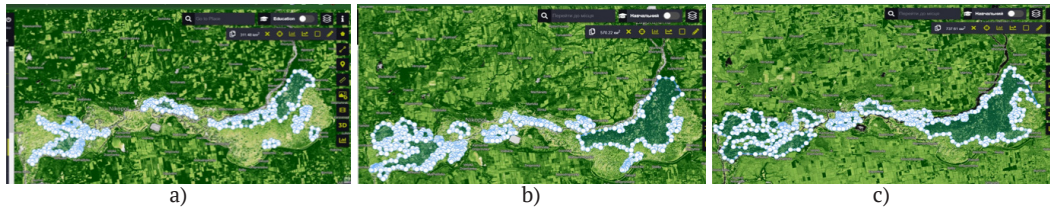


Figure 8. Dynamics of biomass area growth in the Kakhovka Reservoir

Note: a) 2023-08-19; b) 2023-09-08; c) 2023-11-07

Source: EO Browser software, Sentinel-2 L2A satellite

Based on the study conducted, it was found that the restoration of the historical territory of the dewatered Kakhovka Reservoir, namely the Velykyi Luh, is possible through ecological restoration. This involves the creation of three main biotopes on the reservoir territory, namely Pannonian and Pontic sandy steppes, mesophyllic permanent grasslands of the plains, and floodplain forests. The first biotope is the Pannonian and Pontic sandy steppes (Kuzemko, 2022), which should be created in the eastern, southern, and central parts of the reservoir, as it is mainly formed on less developed soils, while the central, southern, and eastern parts of the reservoir are predominantly sandy plains. It includes the following vascular plants: *Secale sylvestre*, *Carex colchica*, *Festuca beckeri*, *Stipa borysthena*, *Thymus pallasianus*, *Tragopogon borysthenicus*, *Astragalus varius*, *Achillea micrantha*, *Agropyron dasyanthum*, *Jacobaea borysthena*, *Dianthus platyodon*, *Agropyron lavrenkoanum*, *Koeleria glauca* aggr., *Asperula graveolens*, *Centaurea arenaria* aggr., *Euphorbia seguieriana*, *Erysimum montanum*, *Anchusa gmelinii*, *Jurinea longifolia*, *Chondrilla juncea*, *Minuartia viscosa*, *Artemisia campestris* aggr. Bryophytes: *Ceratodon purpureus*, *Polytrichum piliferum*, *Syntrichia ruralis*. Rare species: *Agropyron dasyanthum*, *A. cimmericum*, *Allium savranicum*, *Alyssum*

savranicum, *Carex liparocarpos*, *Centaurea appendicata*, *C. breviceps*, *C. donetzica*, *C. konkae*, *C. margaritacea*. The second proposed biotope is mesophyllic permanent grassland of the plains, which is mainly grassland for grazing (Kuzemko, 2022) in the northern and north-eastern parts of the reservoir, which will provide favourable conditions for livestock. It includes the following vascular plants: *Achillea millefolium* aggr., *Trifolium pratense*, *Lotus corniculatus*, *Trifolium repens*, *Schedonorus pratensis*, *Galium verum*, *Prunella vulgaris*, *Convolvulus arvensis*, *Centaurea jacea* subsp. *jacea*, *Scorzoneroides autumnalis*, *Carex praecox*, *Ranunculus acris* aggr., *Potentilla argentea*, *Medicago lupulina*, *Agrostis capillaris*. Bryophytes: *Thuidium delicatulum*, *Atrichum undulatum*, *Brachythecium rutabulum*. Rare species: *Anacamptis coriophora*, *Carex scacalina*, *Fritillaria meleagroides*, *Gladiolus tenuis*. The following may also grow: *Quercus*, *Populus nigra*, *Malus sylvestris*, *Pyrus communis*, *Betula borysthena*. The third biotope is floodplain forests, which develop on river sediments within the floodplain in the western and eastern parts of the reservoir, where the highest concentration of rivers is found. Floodplain forests can be represented by the following woody and herbaceous plants: *Quercus*, *Pyrus communis*, *Salix*, *Populus nigra*, *Malus sylvestris*, *Betula*

borysthena. *Rorippa brachycarpa*, *Vicia hirsuta*, *Carex melanostachya*, *Elatine alsinastrum*, *Vicia villosa*, *Allium regelianum*, *Dianthus guttatus*, *Phalacrachena inuloides*, *Crepis ramosissima*, *Damasonium alisma*, *Achillea micranthoides*, *Linaria biebersteinii*, *Gratiola officinalis*, *Butomus umbellatus*, including rare plants: *Salvinia natans*, *Trapa natans*, *Nymphoides peltata*, *Aldrovanda vesiculosa*, *Nymphaea alba*, *Nuphar lutea*, *Sagittaria sagittifolia*, *Glyceria arundinacea*, *Ceratophyllum tanaiticum*, *Ceratophyllum submersum* and bryophytes: *Sampyllum stellatum*, *Calliergonella cuspidata*, *Plagiomnium medium*, *Drepanocladus aduncus*, *Fissidens adianthoides*, *Bryum pseudotriquetrum*, *Aulacomnium palustre*, *Thuidium philibertii*,

Global warming, urbanisation, intensification of human activity (drainage reclamation, agricultural use, and chemicalisation of watershed soils, growth of settlement land, uncontrolled extraction of water from underground horizons, unauthorised amber mining, etc.) and great pressure on river ecosystems have led to ecosystem degradation, reduction of biotopes and biodiversity, and loss of their functions. P. Li *et al.* (2022) investigated the application of ecological restoration technologies aimed at improving biodiversity and river ecosystems, which is determined by the research and implementation of innovative approaches. These technologies include methods of restoring natural vegetation, regenerating water basins and managing anthropogenic impacts for the balanced functioning of river ecosystems. The study of this issue reveals the effectiveness and possibilities of using ecological technologies to improve the state of biodiversity and ecosystems in rivers. V.O. Martyniuk & O.V. Tomchenko (2021) considered the use of remote sensing tools in the study of lakes in the Polissia region, which opens the possibility of a detailed assessment of natural and anthropogenic transformations of these water

systems. The analysis of satellite images allows identifying changes in the landscape, as well as the impact of anthropogenic activities on the hydrological and ecological aspects of the lake environment. This innovative approach allows effectively monitoring and responding to changes, contributing to the scientific understanding and effective management of the Polissia region's natural resources.

J. Chenoweth (2006) reflected the establishment of sustainable goals for ecological restoration, using evidence from the restoration of river systems in Israel. The cited study defined concrete and sustainable goals for improving the river environment and developing strategies and technologies to achieve these goals. The implementation of sustainable goals for the restoration of river ecosystems in Israel contributes to improving the quality of natural resources and ensuring environmental sustainability. Y. Zhang *et al.* (2024) found that to combat environmental degradation and promote ecosystem resilience, China made considerable investments in ecological restoration of territories during 2009-2019. They noted that they have identified key aspects and technological tools that have helped to achieve positive results in the field of environmental restoration in this period. The study aims to identify and understand the factors that have determined the success of environmental measures in China and their contribution to the sustainability of natural systems. S. Poikane *et al.* (2024) noted that the most effective and widely used restoration measures target nutrient loading (both in the catchment and in the lake), while hydrological modifications and implementation of natural solutions are less commonly used. According to D. Galea & J.E. Major (2024) from Eastern Canada, ecological restoration is possible even on severely degraded sites in two years, provided the site preparation factor: growth and biomass using four early successional species (*Betula*

papyrifera Marshall., *Betula populifolia* Marshall., *Alnus viridis* Vill. *subsp. crispa* Ait., *Alnus incana* L. *subsp. rugosa* Du Roi.) is used. The scale of ecosystem degradation is enormous: over 75% of the land has been severely altered by human activities, and one million species are threatened with extinction (Alamenciak *et al.*, 2023). According to A. Tamura (2016), who investigated this phenomenon in the forests of eastern Japan, ecological restoration of old wet forests is possible due to seeds staying in the soil.

Ecosystem restoration is not just about protecting wildlife. Nature contributes to humanity's overall health and well-being and provides considerable social and economic benefits. But today we are losing nature at an unprecedented rate (Factsheet 2. Economic..., 2023). To determine the possibility of restoring the flooded historical area – the Velykyi Luh of the Kakhovka Reservoir, which has undergone changes due to anthropogenic impact, the authors conducted a spectral analysis of the territory of the Kakhovka Reservoir. F.H. Alexander *et al.* (2022) note that spectral analysis can be used to determine the characteristics of objects by their reflection or emission in different spectral ranges. The spectra of vegetation have two general forms: green and moist (photosynthetic) and dry non-photosynthetic. Green vegetation has an absorption of less than 1 μm due to chlorophyll. Those with a wavelength of more than 0.9 μm are dominated by liquid water. Dry vegetation shows an uptake dominated by cellulose, as well as lignin and nitrogen. R.A. Ryerson & A.N. Rencz (1999) analysed the use of remote sensing in land management sciences, which is determined by its powerful potential for collecting information about the Earth. This method helps to obtain data from a large area, studying various aspects of geology, hydrology, and other branches of Earth science. The use of remote sensing in land management studies helps to analyse the dynamics of chang-

es in natural processes and the interaction of various ecosystem components.

The ecological restoration of the Kakhovka Reservoir to restore the Velykyi Luh is considered a vital step in preserving natural diversity and restoring lost ecosystems. This process involves not only the restoration of natural vegetation, but also active consideration of natural processes and the wetland environment. The spectral analysis and investigation of the territory's characteristics, carried out using modern methods, help to create scientifically based approaches to restoration, contributing to the sustainable development of the Velykyi Luh ecosystem at the Kakhovka Reservoir.

Conclusions

The destruction of the Kakhovka HPP is an environmental crime with grave consequences for the Ukraine. The territory of Velykyi Luh is an important historical monument of the Ukraine and needs to be restored. By analysing the water surface dynamics from 1990 to 2010 using the NDWI, it was found that for 30 years the water surface of the Kakhovka Reservoir stayed almost unchanged until the moment of the explosion. Using NDVI, NDMI, and NDWI together with satellite images in the EO Browser software, it was possible to determine the dynamics of the water surface and vegetation, considering the moisture availability in the reservoir area. By quantifying green biomass and determining the moisture content of the vegetation on the territory of the Kakhovka Reservoir, it was found that gradual dehydration led to a stressful state of plants around the reservoir, which only increased from 6 June to the end of 2023. The NDVI and NDMI indices are dynamic and demonstrate the consequences of the damaged area as a result of anthropogenic impact and its recovery. The green biomass, which has increased by 237% since the dewatering, contributes to the formation of the necessary water balance. Based on the analysis

of historical sources, three biotopes (Pannonian and Pontic sandy steppes, mesophyllic permanent grasslands of the plains, and floodplain forests) were proposed to help restore the historical territory of the Velykyi Luh. It was found that based on the analysis of images and moisture indices, focusing on the state of vegetation and water resources, it is possible to effectively select biotopes for ecological restoration. Presently, nature is initiating its own process of regeneration of the Velykyi Luh, and without active human involvement, the restoration of this historic area is unlikely.

Future research may be aimed at continuing to monitor the dynamics of vegetation biomass growth after the ecological restoration of the dewatered part of the Kakhovka reservoir, as well as the dynamics of the restoration of the Velykyi Luh river network.

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None.

Conflict of Interest

The authors of this study declare no conflict of interest.

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Відновлення Великого Лугу шляхом екологічної реставрації Каховського водосховища

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Анотація. Актуальність сучасної екологічної проблематики вимагає комплексних підходів до відновлення та збереження природних екосистем, зокрема через використання екологічної реставрації як інструменту для усунення наслідків антропогенних втручань. Мета дослідження – обстежити територію Каховського водосховища за допомогою дистанційного зондування Землі та запропонувати спосіб відновлення історичної території Каховського водосховища Великого Лугу. Застосовано методи досліджень: емпіричні, аналіз і систематизація, дистанційне зондування Землі, геоінформаційні системи. Дослідження складалося з двох основних етапів. Перший етап включав аналіз динаміки історичної території Великого Лугу, з кінця XIX століття до нині. Другий етап передбачав порівняння динаміки відновлення даної території, використовуючи картографічні дані XIX століття та супутникові знімки XXI століття. Застосування сучасних технологій, зокрема аналіз супутникових зображень деградованої території та трьох індексів програмного забезпечення EO Browser, таких як диференційований вегетаційний індекс, нормалізований диференційний індекс вологості, диференційний індекс води, дозволило отримати дані щодо стану рослинності та водних ресурсів на досліджуваній території. Аналіз закономірностей між цими показниками дозволив визначити тісну взаємодію між темпами зростання рослин та їх вологозабезпеченістю. Було виміряно приріст біомаси на території Каховського водосховища з моменту зневоднення до листопада 2023 року. Отримані результати вказують на можливість ефективного відновлення екосистеми Великого Лугу шляхом екологічної реставрації. Цей процес передбачає вибір оптимальних біотопів для відновлення історичної місцевості, що є важливим кроком у збереженні біорізноманіття та стабілізації природного середовища на території Каховського водосховища. Результати досліджень із застосування нового підходу до екологічної реставрації, що базується на високоточних технологіях та глибокому аналізі динаміки екосистем сприятимуть розвитку наукових підходів до відновлення природних ландшафтів і стануть важливим внеском у сучасну екологічну практику

Ключові слова: дистанційне зондування землі; рослинність; екологія; регенерація; історична місцевість

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Strategies and challenges of artificial forest reproduction in the forest-steppe zone: Experience of the Korsun-Shevchenkivskiy forest enterprise branch

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Abstract. One of the key problems that arise in the reproduction of forests in the paradigm of sustainable development of the forest industry is the volume of reforestation, which requires its correlation. This problem requires attention, since effective afforestation and reforestation determine the stability of the ecosystem and the importance of forest resources for the conservation of biodiversity in the forest sector. The purpose of the study is to investigate the features of artificial forest reproduction in the conditions of the forest-steppe climatic and geographical zone. The methodological basis for organising observations included field survey of planting material plots,

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monitoring the state of crops on the area, conducting analytical substantiation of progressive experience, and evaluating the final results obtained. The study was conducted in the Korsun-Shevchenkivskiy forest enterprise branch of the state enterprise "Forests of Ukraine". The dynamics of annual volumes of artificial forest reproduction, considering the predominant tree species during 2012-2021, is presented. Additionally, the advantages and disadvantages of transplanting of main and related species in the presented forest conditions were analysed. During this period, there is a fluctuation in the volume of artificial forest reproduction in the forest districts under study. With regard to the transplanting of main and related species, it is worth noting its advantages in ensuring biodiversity and rapid forest regeneration. However, there are disadvantages, such as the possibility of losing genetic diversity and considering local conditions for effective seating. As a result, the study helped to determine the trends and features of forest reproduction in these forest districts, and to note the advantages and disadvantages of transplanting of the main and related breeds in various forest-growing conditions. The enterprise is actively implementing measures for forest reproduction, focusing on intensive planting of forest crops. This is achieved by placing plantations in areas that have been subjected to continuous sanitary and reforestation logging. One of the key tasks of the enterprise is to ensure high productivity of forest crops in the region. For this purpose, significant amounts of reforestation work are carried out, including systematic soil preparation and careful selection of optimal species for specific conditions. Considering the recommendations of forest management, an integrated approach to reforestation is reflected, which ensures sustainable and productive ecosystems in the region. The developed strategies can serve as an important tool for introducing innovations in the field of forestry

Keywords: forest conditions; transplanting; forest crops; reforestation; productivity of forest crops

Introduction

The issue of restoring forest resources, in particular their expansion to increase the share of forest cover in Ukraine, closely correlates with significant tree felling, the impact of planetary climate changes, shifting groundwater levels, floods that provoke natural and other disasters. Therefore, it is logical that in modern conditions, the restoration, preservation and reproduction of forests is considered by the world establishment as a guarantee of an environmentally stable future of humanity. The implementation of the model of sustainable development of the forest industry can be successful only if the main problems inherent in Ukrainian reforestation and afforestation are solved. The key tasks are to overcome these problems and ensure the systematic reproduction of forests in sufficient volumes, which is a necessity today.

Among the key problems in forest reproduction in the paradigm of sustainable development of the industrial sector, a small share of afforestation and reforestation at the proper level is singled out. Insufficient afforestation makes it difficult to maintain forest cover at the required scientifically proven level in certain regions of the country. High-quality reforestation, in particular artificial, even with sufficient regulatory measures, it is not possible to guarantee the reproduction of full-fledged forest cenoses, in particular, the creation of ecosystems with high biological resistance, which are as close as possible in composition and shape to natural stands.

The search for new ways of a balanced ecological and economic approach in forestry in the context of sustainable development is highlighted in the studies by O. Furdychko *et*

al. (2021a; 2021b), that present a multi-factor model for predicting the state of forest ecosystem recovery by 2035. The researchers point to the fact that the social aspect of the balance of forest fund use in Ukraine is determined by the impact of forestry on the local population. Ensuring social responsibility in forestry involves balanced access to forest resources for local communities, providing jobs and community participation in forest management decisions. An important aspect is the preservation of traditional forest use and the promotion of rural development through effective forest management. M. Sobkowiak *et al.* (2020) reviewed the implementation of government programmes for biodiversity conservation and the importance of climate change for forest management decision-making. The researchers focused on exploring the relationship between conservation strategies and climate change adaptation strategies, providing important insights into how these two aspects interact in shaping effective forest management. The results of their study point to the need to integrate biodiversity and climate change adaptation strategies to create more integrated and sustainable forest management.

A number of researchers pay considerable attention to the problems of natural renewal of oak forests during logging of the main use in protective and recreational forests. I.S. Neyko *et al.* (2022) found that the main objectives of afforestation and reforestation in the future are to increase forest area by restoring natural ecosystems and preserving existing forests. To do this, it is necessary to take measures for forest planting, creating new tree stands, and ensuring proper care at all stages of development. An important task is to introduce modern methods of forestry aimed at preserving natural resources and balanced use of forest biogeocenoses.

In the study by R. Hazarika *et al.* (2021), reforestation is seen from the perspective of species introduction as a way to increase forest

cover, in particular, through genetic diversity of forests and national legislation on trade and use of forest reproductive material (FRM) are key aspects of forest management and adaptation to climate change in European countries.

Changes in forest cover are a major factor in local climate change around the world, as they affect both albedo and evapotranspiration (ET). Deforestation and afforestation are expected to have opposite effects on surface albedo and ET rates, and thus have different effects on Earth's surface temperature (Prevedello *et al.*, 2019).

The process of implementing large-scale afforestation projects should consider global changes in circulation and their impact on the remote climate. R. Portmann *et al.* (2022) analysed national datasets for tree species *Picea abies*, *Pinus sylvestris*, *P. pinaster*, *Fagus sylvatica*, *Fraxinus excelsior*, *Quercus robur*, *Q. rubra*, and *Q. Petraea*. Given the large number of species under consideration, it is important to note that the impacts of afforestation and deforestation on climate are complex and depend on specific ecosystems and geographical conditions. Understanding these processes is key to effective forest management and maintaining climate sustainability on a global scale.

S. Jansen *et al.* (2019) discussed the estimated genetic impact of transferred FRM (forest reproductive material) on local tree populations, reviewed legislation and documentation processes for their compliance. The study by S. Jansen *et al.* (2019) examined in detail the putative genetic effects of transferred FRM (forest reproductive material) on local tree populations. The researchers covered not only scientific information, but also considered important aspects of the legislative environment and documentation processes to ensure that the use of FRM meets the requirements of laws and regulations. An important element of the study was the investigation of the influence of transferred forest reproductive material on the genetic structure of local tree populations. The

researchers identified which aspects of genetic diversity can be changed or improved by implementing FRM, and considered possible impacts on ecosystems and the cost of biodiversity. In the context of reviewing legislation and documentation processes, the researchers determined what rules and requirements should be considered when using transported FRM. This is important for ensuring long-term sustainability and effective management of forest resources, and for ensuring compliance with the health and development of local tree ecosystems.

The purpose of the study was to investigate the characteristic features of artificial forest reproduction in the climatic and geographical region of the forest-steppe.

The objective of the study was to characterise the dynamics of annual volumes of artificial forest reproduction in the Korsun-Shevchenkivskiy forest enterprise by the predominant tree species; to highlight the advantages and disadvantages of transplanting of the main and related species in the specified forest conditions.

Materials and Methods

The study was conducted during 2012-2021 on the territory of Vyhraiv, Kvitky, Kumeiky, Korsun, Tahancha, and Yasnozirya forestry sections (Korsun-Shevchenkivskiy forest enterprise branch, Cherkasy Oblast, Ukraine). The paper used a variety of resources and methodologies for a comprehensive analysis of the research subject. The theoretical approach involved analysing, synthesising, deducing, inducing, comparing, concretising, and generalising scientific sources related to the contextual problem. Additionally, the study of regulatory documents (project of the forestry development organisation) (Ukrainian State Design Forestry Production Association, n.d.) related to the object of research was conducted. The empirical method included such methodological foundations as the organisation of observations (field survey of planting material plots, monitoring of the state of crops on the area), the of analytical

substantiation of progressive experience, the assessment of the final results, and the description of the structure of the subject matter. For objective data collection and their subsequent analysis to obtain comprehensive information on the state of the forest ecosystems, empirical research tools were used (collection of actual data, generalisation, systematisation, in particular, forestry and ecological ones – when studying the typological characteristics of forest plantations; generalisation – to record the general features of a certain set of objects and to make a transition from the individual to the general, that is, to generalise the results of research; by visual assessment of seedlings on the plantation, description of the research object). Methods of detection, including field mapping, and interpretation, including functional and analytical methods, were also used to study the structure of the vegetation cover. To analyse the current stages of growing forest crops and investigate the features of phytocenoses of pine forests of the Korsun-Shevchenkivskiy forest enterprise branch, early office analysis was carried out. Based on the forest management documentation of the enterprise, it was determined that the most characteristic site is located on the territory of the Korsun-Shevchenkivskiy forest enterprise, and this served as the basis for determining the study areas. The research was conducted in compliance with the Convention on the Trade in Endangered Species of Wild Fauna and Flora (1973) and the Convention on Biological Diversity (1992).

Forest nurseries are an integral part of the forestry process of the Korsun-Shevchenkivskiy forest enterprise branch. In particular, the Kumeiky forestry established a sowing department and a decorative nursery of a temporary forest nursery, where 1-2-year-old Scots pine seedlings and 2-year-old European spruce seedlings grow (Fig. 1). In the temporary nursery of the Kvitky forestry, annual seedlings of common oak and northern red oak were grown (Fig. 2, 3).



Figure 1. General view of the temporary nursery of the Kumeiky forestry

Source: photo by O. Zabrodotskyi, I. Chemerys

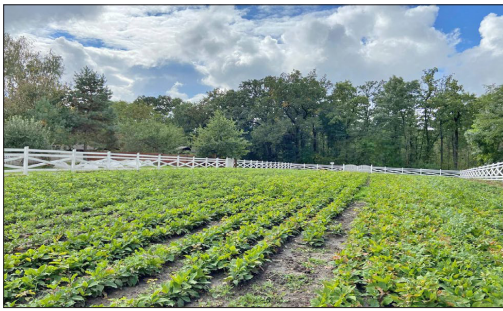


Figure 2. General view of the temporary nursery of the Kvitky forestry section

Note: general view of forest crops with a predominant tree species of common oak established in spring 2022

Source: photo by O. Zabrodotskyi, I. Chemerys



Figure 3. General view of forest crops after mechanised care in the row spacing of forest crops by MTZ-82 tractor (Belarus), combined with Kansas-170 (Ukraine)

Note: the photo shows 4-year-old cultures of common oak, Kvitky forestry

Source: photo by O. Zabrodotskyi, I. Chemerys

This strategic decision was aimed at improving the sustainability and productivity of forest ecosystems in the region. The period of transition of forest crops to land covered with forest vegetation was determined for about 6-7 years, depending on the main species. Soil preparation included furrowing with an MTZ-82 tractor (Minsk Tractor Works, Belarus) using a PKL-70 combined forest plough (SPETSLISMASH LLC, Ukraine). This process took place in September-November for spring planting and in August for autumn planting. 2-3 weeks before planting forest crops, deep nonmouldboard cultivation of the soil was carried out, while nitrogen fertilisers were applied at the rate of 70 kg/ha of ammonium nitrate. For these works, the MTZ-82 tractor (Minsk Tractor Works, Belarus) was used in combination with RN-60.80 tractor-mounted ripper (LLC SPETSLISMASH, Ukraine). In the areas where the cover of mardones and other cereal plants was found, herbicides with contact action from the glyphosphate group, such as Clinic, Roundup, Felix, and Uragan-Forte, were applied. The dosage was 3-7 litres per 1 hectare of active substance. To carry out these activities, an MTZ-82 tractor (Minsk Tractor Works, Belarus) with an ON-400 mounted sprayer was used by spraying the drug on the leaf surface during the growing season and vegetation height of 20 cm or above. Planting of crops was carried out using Kolesov's planting iron. Annual seedlings of Scots pine, common oak, northern red oak, black walnut, and black locust tree, obtained from their own nurseries, were used for planting. In the areas where multi-age May beetle larvae were recorded, material with a root system treated with Prestige or Aktara preparations was used during planting. Forest crops received care for five years according to a specific scheme, which provided for a gradual reduction in the intensity of work: starting with five rows of row spacing and mechanised cultivation using MTZ-82 (Minsk Tractor Works, Belarus) with KLB-1.7 combined forest plough (LLC SPETSLISMASH, Ukraine),

the row spacing was reduced at each subsequent stage. The lines were handled manually throughout the period. In addition, with a mortality of more than 15%, the addition of forest crops with the main species was carried out to maintain the sustainability of the ecosystem and ensure optimal growth. Possible areas for improving forest culture activities at the enterprise include the following aspects: expansion of work aimed at natural renewal, especially in conditions that contribute to this; implementation of furrowing to promote the natural renewal of forest tree species; use of high-quality planting material with improved hereditary properties; use of plants with a closed root system to ensure better survival and development; establishment of a seed bank for storing and using seed material in lean years; effective use of internal reserves to ensure sustainable seed production and reduce dependence on purchases. These areas are aimed at optimising the processes of forest culture activities, preserving biodiversity and ensuring the sustainability of forest ecosystems at the enterprise.

Results and Discussion

The technological process of creating forest crops is a complex of agrotechnical, silvicultural, sanitary and protective and other techniques aimed at growing forest crops with the help of machines, materials, mechanisms, as well as organising their implementation. Agrotechnical methods of planting forest crops are determined by various factors, such as the nature of the terrain, the type of forest conditions, and the category of forest-cultivated area. Silvicultural techniques are determined by the orientation of plantation in accordance with its intended purpose. Biological methods include the use of pest control products.

Sanitary protection techniques include the implementation of sanitary selective logging and other measures to improve the condition of forest stands. The Korsun-Shevchenkivskiy forest enterprise branch has improved and implemented agricultural techniques for growing planting material in forest nurseries in forest-steppe conditions. This technology must be considered and followed at all stages of the production process. Conventional methods of sowing in beds have been replaced by new approaches that involve the use of longitudinal rows and strips. This decision is substantiated by studying the optimal parameters for seedling placement, growth, and development. Seeding rates, optimal sowing depth, timing and structure of crops were established. The efficiency of using fertilisers in the corresponding geographical areas of Ukraine, to ensure optimal plant nutrition and increase yields, was considered. All these measures are aimed at improving the quality and quantity of planting material obtained, and optimising agricultural processes in forestry (Debryniuk, 2013).

The existing nurseries on the enterprise almost completely meet the needs for planting material. The sowing department uses breeding material collected from family and clone plantations, and from permanent and temporary forest seed plots. Based on the average annual production volumes of forest crops, the required volume in planting material is calculated, which corresponds to 95.1 thousand seedlings. This indicator is considered to determine the area of the sowing and nursery departments. In the sowing sector of the nursery, the following species are grown: Scots pine (*Pinus sylvestris* L.), common oak (*Quercus robur* L.), black walnut *Juglans nigra* L.), northern red oak (*Quercus rubra* L.) (Table 1).

Table 1. Dynamics of annual volumes of artificial forest reproduction in the Korsun-Shevchenkivskiy forest enterprise branch by predominant tree species during 2012-2021

Year of establishment	Planting and sowing forest								
	incl. by predominant tree species								Total, ha
	Scots pine		Common oak		Black walnut		Northern red oak		
	ha	%	ha	%	ha	%	ha	%	
2012	75	61.9	21.1	17.4	11.2	9.2	13.8	11.4	121.1
2013	115.6	82.5	16.9	12.1	5.6	4	2	1.4	140.1
2014	102.6	79.7	21.6	16.8	4.5	3.5	-	-	128.7
2015	136	85.3	13.4	8.4	10.1	6.3	-	-	159.5
2016	141.2	81.7	18	10.4	13.6	7.9	-	-	172.8
2017	140.3	86.3	15.6	9.6	6.6	4.1	-	-	162.5
2018	75.5	72.9	25.4	24.5	-	-	2.6	2.5	103.5
2019	57.3	64.6	30.9	34.8	0.5	0.6	-	-	88.7
2020	63.8	63.4	35.8	35.6	1.1	1.1	-	-	100.7
2021	43.5	50.3	36.4	42.1	6.6	7.6	-	-	86.5
Total	950.8	75.2	235.1	18.6	59.8	4.7	18.4	1.5	1,264.1
Average for 10 years	95.1	75.2	23.5	18.6	6.0	4.7	1.8	1.5	126.4

Note: includes the volumes of reproduction of Vyhraiv, Kvitky, Kumeiky, Korsun, Tahancha, and Yasnoziryva forestry sections

Source: developed by the authors based on the Ukrainian State Design Forestry Production Association (n.d.)

Forest transplanting has its advantages, in particular, the possibility of planting already grown plants on forest-cultivated areas that can immediately compete with grass vegetation. However, planting seedlings or saplings is often used to establish forest cultures, as this simplifies the care process and ensures a certain level of plant safety. Among the disadvantages of transplanting, there are significant costs associated with the cultivation of planting material, namely: the creation, maintenance, selection, and transportation of seedlings, and the payment of wages to employees.

In the context of this forest enterprise, three main methods of artificial reproduction of forest crops are defined: sowing, planting,

and a combination of both previous methods. In the future, it is planned to recreate forest ecosystems by artificial plantings on the edges of logging sites within the forest fund of enterprise on a total area of 638.6 hectares, while natural restoration was planned on a total area of 225.3 hectares. Forestry has actually completed work on an area of 2,493.1 hectares, including 655.3 hectares of natural regeneration. There are no protective forest plantations on lands unsuitable for agricultural production, which are not included in the area of the forestry enterprise due to the lack of regulatory and economic documents confirming the right to permanent use of land (Table 2).

Table 1. Implementation of the main types of forest restoration work in 2014-2023

Main types of work	Total, ha	Average annual implementation in ha	
		2014-2023	in the year preceding the current forest management
1. Reproduction of forests, total, incl.	2,493.1	249.3	255.1
◆ forest sowing	-	-	-
◆ forest planting	2,493.1	249.3	255.1
2. Reforestation:	2,360.5	236.0	235.0
◆ incl. reconstruction of plantations	-	-	-
3. Afforestation:	132.6	13.3	20.1
◆ in clearings, wastelands,	132.6	13.3	20.1
◆ on unsuitable land of other land users	-	-	-
4. Natural renewal	655.3	65.3	55.8
5. Creation of protective forest stands on the lands of other users	-	-	-
◆ including shelterbelts	-	-	-
6. Sowing seeds of tree and shrub species in nurseries	21	2.1	2.1
7. Planting of seedlings of tree and shrub species in nurseries	10.0	1.0	1.0

Source: developed by the authors based on the Ukrainian State Design Forestry Production Association (n.d.)

Forest management measures related to reforestation methods, selection of the main species, soil preparation under 84% mechanisation conditions, and types of forest crops are carried out at the proper level at the enterprise. However, it is necessary to introduce additional techniques for creating forest crops for such species as northern red oak, European spruce, European larch, common ash, black walnut, and black alder in the forest fund of the forestry enterprise on an area of 156.7 hectares or 16.5%. This will improve and enrich the diversity of species in the created forest plantations, which also corresponds to the types of growing conditions of these tree species. Forest crops are planted using two methods: 70% of the area is planted manually, and 30% using mechanised means. During 2012-2021, ten treatments of forest crops was carried out. In total, during this period of time, an area of 3,901.6 hectares was cultivated, which is 106% of the planned volume. The mechanised approach to crop care is 8.7%. The system of measures aimed at

forest crops in recent years has covered the use of a chemical method on a total area of 76.0 hectares. In 2012, Uragan-Forte (active ingredient: glyphosate) was used in forest crops of Scots pine on an area of 17.2 hectares. The main species were added to forest crops when the mortality was 15% or more. On average, additional measures were implemented annually on a total area of 205 hectares. The number of plantings and mixing schemes of forest crops correspond to the technological schemes that were designed as part of forest management. The timing of the transfer of forest crops to forest vegetation is carried out in accordance with the established regulatory documents (Fuchylo & Kyrylko, 2022; Kychylyuk *et al.*, 2022).

Forestry enterprise facilitated the natural renewal, in particular, by fertilising the soil with minerals on an area of 305.3 hectares on plots during logging of the main use. However, the implementation of these events did not always lead to the desired result. The transfer of forest plots to those covered with forest

vegetation after the implementation of measures to promote natural renewal in the forestry enterprise did not take place.

The production site designed reconstruction of low-value and low-top plantings on an area of 34.3 hectares, including continuous reconstructive logging on 34.3 hectares. The next step is to create forest plantations of common oak on the same area. Practical restoration was carried out on an area of 33.0 hectares of black locust trees. It is important to note that the implementation of this economic measure did not significantly improve the species composition and expected changes in the derived stands. It was planned to carry out natural renewal on an area of 225.3 hectares, of which 200.2 hectares were provided in cutting areas of audit design.

Natural recovery was observed with the participation of black locust tree and black alder in open forest areas and cutting areas devoid of forest vegetation on a total area of 402.3 hectares. In particular, black locust tree successfully populated the slopes of various exposures, while black alder prevailed in conditions with high humidity levels. These natural processes gave positive results and did not cause changes in the main species, given the specific natural conditions. The satisfactory condition of forest

crops of the 1st and 2nd quality class in unclosed forest areas is 83.1%, while in areas converted to forest grasses, this class is only 62.4%. It is important to note that no unsatisfactory forest crops were found, which indicates the effectiveness of silvicultural work in the enterprise. This was achieved due to the timely implementation of measures to restore plantings on logging sites of the main use and sanitary logging of valuable forest-forming species. Care at a sufficient level with the necessary agrotechnical techniques also plays an important role in ensuring the stable condition of forest crops.

The forestry enterprise needed an average of 5,285.0 kg of seeds to perform reforestation operations over the past two years. Seed collection was carried out from isolated trees with the best condition, located in parks, forest strips and on permanent seed plots. The total amount of seeds harvested over the past two years is 4,324.0 kg, of which 33.5% were collected on permanent seed plots for common oak. It is also important to note that some of the seeds were imported from other districts of the region (Table 3). The forestry enterprise has created a permanent forest seed base for the purpose of growing high-quality planting material with valuable hereditary properties (Table 4).

Table 3. Dynamics of forest seed harvesting volumes in the state enterprise Korsun-Shevchenkivskiy forest enterprise during 2012-2021

Tree species	Harvested seeds per year, kg									
	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Common oak	1,300	1,500	1,700	3,763	3,040	565	3,130	3,390	3,700	6,450
Northern red oak	958	1,060	920	400	2,690	2,432	1,300	980	1,600	1,600
Black walnut	2,500	3,099	2,840	2,480	3,110	2,870	1,933	2,108	1,906	2,920
Common walnut	–	–	–	–	–	108	62	60	58	120
Scots pine	160	150	179	111	100	129	70	51.5	59.3	43.1
Other	20	20	15	10	10	10	–	28.5	26.5	13
Total	4,938	5,829	5,654	6,764	8,950	6,114	6,495	6,618	7,350	11,146
From them for PSP	–	500	300	–	500	–	–	500	1900	500

Note: PSP –permanent seed plantation

Source: developed by the authors based on the Ukrainian State Design Forestry Production Association (n.d.)

Table 3. Availability of planting material according to the balance (2013-2022)

Balance for spring, year	Standard seedlings and rooted cuttings, thousand units					
	availability according to the autumn inventory	used in autumn for planting, supplementing, and selling	availability as of January 1 of the reporting year	need for everything	balance	
					excess	shortage
2022	684.7	184	500.7	445.7	55	–
2021	725.2	114.4	610.8	608.4	2.4	–
2020	1,001.6	–	1,001.6	903.3	98.3	–
2019	1,187	229	958	816.9	151	9.9
2018	1,177	312	865	815	50	–
2017	1,264	250	1,014	977	69	32
2016	1,777	290	1,487	1,541.2	–	54.2
2015	1,221	138	1,083	1,102	–	19
2014	1,098.9	171	927.9	950.7	0.2	23
2013	2,010.6	184.6	1,826	1,526.8	355	55.8

Source: developed by the authors based on the Ukrainian State Design Forestry Production Association (n.d.)

From the presented statistical results (Table 3) it can be seen that the dynamics of the volume of harvesting of forest seeds increased significantly in 2021, increasing from 111% to 500% compared to 2012. However, the volume of pine seed harvesting in 2021 decreased by 27% compared to 2012.

At the enterprise, there are nurseries with a total area of 4.6 hectares, of which 1.0 hectares are intended for temporary use. The productive area of nurseries is 4.5 hectares, and the average annual number of seedlings grown over the past two years is 379.5 thousand units. Of this total number: 11.6 thousand units of Scots pine; 5.2 thousand units of Crimean pine; 9.2 thousand units of European spruce; 0.5 thousand units of larch; 2.7 thousand units of northern white cedar; 4.5 thousand units of juniper; 0.3 thousand units of other species; 96.7 thousand units of common oak; 0.6 thousand units of Norway maple; 22.9 thousand units of small-leaved linden; 190.8 thousand units of black locust tree; 5.8 thousand other tree species; 28.7 thousand units of shrub species.

The forestry uses two greenhouses with an area of 447 m² to grow planting material. An average of 43.15 thousand plant cuttings with a

well-developed root system are grown in these greenhouses annually, which are then used for decorative purposes. In particular, this applies to seedlings of common box, European spruce, northern white cedar, Scots pine, common juniper, and common ninebark. Currently, the existing nurseries in the forestry enterprise fully produce the necessary amount of planting material, and therefore, their further expansion is not planned. Planting material that is grown in forest nurseries finds its application to improve the condition of forest crops and landscaping the territories where the forestry enterprise is located.

The forest fund of Ukraine corresponds to an area of 10.4 million hectares, which nowadays has a significant predominance of artificial plantations – forest crops – over natural formations.

V.M. Maurer (2012) noted that the state of provision of planting material for reforestation in Ukraine now requires attention and analysis. One of the key problems is the lack of availability and variety of planting material for the restoration of forest areas. It is necessary to address the issue of providing high-quality and adapted seedlings of the main tree species that play an important role in reforestation. In addition, it is important to improve planting technologies

and introduce new methods to improve the efficiency and sustainability of reforestation. The development and implementation of national strategies and programmes aimed at improving the supply of planting material are identified as priority tasks for the conservation and restoration of forest cover in Ukraine (Hensiruk, 2002).

A.N. Nekos & M.Z. Rego (2015) present an approach to identifying high conservation value forests (HCVF). It is determined that the main principles of conservation and reproduction of forest resources aimed at improving the environmentally useful properties of wood are the achievement of environmentally oriented forest management with the study and consideration of forest resources depending on zoning and integrated ecological and economic forest management with environmentally advanced technologies.

Using a high-resolution spatial analysis of global drylands, 448 million hectares suitable for afforestation were identified, and the concentration of forestry in areas with a net cooling effect alone would use up half the area and double the compensation for emissions, report S. Rohatyn *et al.* (2022). This discovery not only highlights the significant opportunities for forest growth in the country, but also highlights the need for strategic planning and priority measures to promote forestry. The application of this approach in forest management can become a key area for a balanced approach to solving problems and setting priorities in the field of providing planting material for forest restoration in Ukraine. In the fight against global climate change, in order to restore biodiversity and increase the income level of local residents around the world, forest planting activities are being accelerated. While afforestation programmes can mitigate not only global climate change itself, but also its adverse effects in the form of drying out, report A. Staal *et al.* (2024). Reforestation in Europe is increas-

ing summer precipitation locally, according to a new analysis of precipitation measurements across the continent. These programmes are becoming a key tool for managing the carbon cycle and conserving water resources, providing a positive impact on biodiversity and the local environment. Effective afforestation is expected to help restore ecosystems and create a sustainable, carbon-neutral environment, which will help counteract climate change and ensure balanced development for local communities. J. Baker (2021) argues that real tree planting levels can mitigate future droughts that are expected due to climate change. Tree planting is defined by the researcher as an effective measure in the fight against droughts, since the forest cover can affect the hydrological cycle and the storage of ground water. Given that trees release less water during the transpiration process in winter than plants in summer, they can affect the reduction of evaporation and, consequently, the storage of moisture in natural ecosystems. The results of this study highlight the importance of careful planning and implementation of tree planting programmes as part of a strategy to adapt to climate change and overcome its negative impacts, in particular, in the form of droughts.

The problems of reforestation and afforestation in the lowland part of Ukraine are given attention in a number of scientific and practical studies, which reveal the features of technological processes for the establishment of forest stands. In particular, O.T. Danchuk (2004) investigated aspects of factors affecting the biological stability of forest biocenoses involving introducers, and possible changes in the genetic structure of populations of native and introduced breeds during reforestation activities. Determining the impact of introduction on biodiversity and interactions between different species, O.T. Danchuk (2004) identified key aspects that determine the sustainability

and long-term sustainability of ecosystems. The study points to the need to consider genetic aspects in reforestation programmes and strategies to preserve natural biodiversity and improve ecosystem sustainability in forest management. V.I. Bilous (2009) made a significant contribution to understanding the features of growing and breeding common oak in the forests of Ukraine. The researcher focused on a detailed investigation of the biological and forest properties of this species, considering intraspecific variability and identifying outcomes that are important for further breeding and management of forest resources. The studies by V.I. Bilous (2009) and Y. Yelisavenko *et al.* (2023) highlight how important it is to consider common oak as a key element of forestry, given its multifaceted characteristics. The results of the study open up new opportunities for optimising the management of this species and developing breeding strategies.

The natural conditions of the region under study create favourable soil and climatic conditions for the successful cultivation of highly productive pine stands, and other valuable tree species. In modern conditions, the production of forest crops must necessarily be aimed at using methods of restoration and afforestation based on the principles of close to nature forestry. This includes the creation and cultivation of biologically sustainable plantings, considering the conservation of natural resources and biodiversity. The enterprise carries out practical complete independent harvesting of seeds, but in case of its insufficiency, purchases are made from neighbouring enterprises. The grown planting material almost all corresponded to standard sizes, which made it suitable for planting on forestry plots. The enterprise performed a significant amount of reforestation work, in particular by increasing the volume of forest crops planted. This was achieved by creating forest crops in areas

where continuous sanitary and reforestation logging was carried out. The recommendations of forest management regarding reforestation methods, soil preparation, and rock mixing were mainly considered and implemented by forestry enterprises. The company's task was to ensure high productivity of forest crops in the region. To achieve this goal, significant amounts of reforestation work have been carried out, including soil preparation and selection of optimal rocks. An important aspect was the consideration of fresh hornbeam-oak-pine subor forest types, where an increase in the area of Scots pine and a decrease in common oak were substantiated.

Conclusions

The Korsun-Shevchenkivskyi forest enterprise branch effectively implements agrotechnical techniques for organising production activities in forestry. The enterprise considers the topography, type of forest conditions, and category of forest area when creating forest plantations. Forestry measures include the establishment of plantations in accordance with their intended purpose, the use of pest control products, and sanitary protection measures. Agricultural techniques for cultivating planting material in forest nurseries were introduced, and bedding methods were replaced. Analysis and rationing of seed sowing was carried out based on geographical conditions. The reforestation programme planned to reforest 638.6 ha, while the enterprise actually implemented the programme on 2,493.1 ha.

Forest management activities include felling, selection of main species, and soil preparation with a high level of mechanisation. Deviations from the project were recorded for some species, which contributed to their diversity. Planting of forest crops was carried out manually and technically. 10 treatments were carried out, which is 106% of the planned amount.

The use of machinery during maintenance was 8.7%. Chemical treatment was carried out on 76.0 ha. Promotion of natural forest regeneration through soil mineralisation on 305.3 ha has not always been successful. Forest nurseries are almost completely provided with planting material using breeding material.

The disadvantages of transplanting are the cost of growing planting material. Planting can take place in a variety of ways, including seedlings and saplings, which can affect the amount of care required.

Further research will focus on finding effective methods for managing forest resources to ensure their sustainability and use in an environmentally balanced way, and developing strategies for preserving soil cover and water resources in the forest-steppe zone.

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Conflict of Interest

None.

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**Стратегії та виклики штучного відтворення лісів
в умовах лісостепової зони:
досвід філії «Корсунь-Шевченківське лісове господарство»**

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Анотація. Серед ключових проблем, що виникають у відтворенні лісів у парадигмі сталого розвитку лісової галузі, варто відзначити обсяг лісовідновлення, який потребує його кореляції. Зазначена проблема вимагає уваги, оскільки ефективне лісорозведення та лісовідновлення визначають стабільність екосистеми та важливість лісових ресурсів для збереження біорізноманіття лісового сектору. Метою роботи є детальне вивчення особливостей штучного відтворення лісів в умовах Лісостепової клімато-географічної зони. Методологічні засади організації спостережень включали польове обстеження ділянок садивного матеріалу, нагляд за станом посівів на площі, здійснення аналітичного обґрунтування прогресивного досвіду, оцінка одержаних кінцевих підсумків. Дослідження проходило в філії «Корсунь-Шевченківське лісове господарство» ДП «Ліси України». Представлено динаміку щорічних обсягів штучного відтворення лісів з урахуванням переважаючих деревних видів протягом 2012-2021 років. Додатково, проведено аналіз переваг і недоліків використання розсадництва головних та супутніх порід в представлених лісорослинних умовах. В зазначений період спостерігається коливання обсягів штучного відтворення лісів у розглянутих лісництвах. Щодо розсадництва головних та супутніх порід, слід відзначити його переваги у забезпеченні біорізноманіття та швидкого відновлення лісів. Однак існують недоліки, такі як можливість втрати генетичної різноманітності та врахування місцевих умов для ефективного розсадження. У підсумку, дослідження дозволило визначити тенденції та особливості відтворення лісів у

вказаних лісництвах, а також відзначити переваги та недоліки розсадництва головних та супутніх порід у різних лісорослинних умовах. Господарство активно впроваджує заходи з відтворення лісів, зосереджуючись на інтенсивному збільшенні обсягів посадок лісових культур. Це досягається завдяки розміщенню насаджень на територіях, які піддавались суцільним санітарним та лісовідновним рубкам. Одним з ключових завдань господарства є забезпечення високої продуктивності лісових культур в регіоні. Для цього виконуються значні обсяги робіт з лісовідновлення, включаючи систематичну підготовку ґрунту та ретельний вибір оптимальних порід для конкретних умов. Враховуючи рекомендації лісовпорядкування, відображено комплексний підхід до лісовідновлення, який забезпечує стійкі та продуктивні екосистеми в регіоні. Розроблені стратегії можуть слугувати важливим інструментом для впровадження інновацій у сферу лісового господарювання

Ключові слова: лісорослинні умови; розсадництво; лісові культури; лісовідновлення; продуктивність лісових культур

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Ulcerative tumour-like disease of white fir in the Pokuttia Carpathians

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Abstract. The current state of dark coniferous forests on Earth is a bio-indicator of global environmental change, in particular, the process of gradual degradation of tree species of the genera Pine, Spruce and Fir, due to the negative impact of anthropogenic activities, abiotic and

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biotic factors. The purpose of the study is to establish the symptoms, prevalence and harmfulness of the causative agent of ulcerative tumour-like disease on the shoots and trunks of white fir. The research was conducted on the territory of the forest fund of the Pokuttia Carpathians, in particular, within the branch Kutske forestry of the State Specialised Economic Enterprise “Forests of Ukraine” in the Kosivske forest enterprise. The study uses classical phytopathological and mycological methods, which are used to investigate the aetiology of the disease, analyse typical symptoms (starting from the early stages), and perform microscopy of the affected parts of fir. The symptoms, aetiology, and pathogenesis of white fir ulcer-like disease, which tends to spread, were investigated. A new name for the disease is substantiated, in particular, it is proposed to use the name “ulcerative tumour-like disease” of fir instead of the current name “cancer”. It is shown that a typical sign of infection is the development of tumours, which eventually transform into ulcers. It was found that the tumour-like type of lesion prevails on the undergrowth of fir, and on plants of the upper tiers – ulcerative. It is noted that a typical sign of ulcerative tumour-like disease of white fir is also the presence of pathologies such as “witches’ broom”. It is proposed to remove affected trees with typical signs of infection with ulcerative tumour-like disease to reduce the infectious background, especially during lighting and cleaning, since affected trees are not released from infection. Therefore, assessing the risk of infection of white fir trees with ulcerative tumour-like disease at the level of specific stands and ensuring an appropriate response to potential infection risks is an important part of sustainable forest management

Keywords: *Abies alba*; rusty fungi; biotic factors; symptoms; aetiology; pathogenesis

Introduction

The problem of dieback of dark coniferous forests with the participation of woody species of genera *Pinus* L., *Picea* A. Dieter and *Abies* Mill. in the world is gaining more and more scale, as their sanitary condition acts as a global biological indicator of environmental changes. Among the main hypotheses of this phenomenon, there are three main factors: abiotic, biotic, and anthropic, which are the foundation of the polyfactorial concept. The impact of abiotic factors, such as climate change and excessive soil moisture, is significant in the process of forest dieback: Biotic aspects, in particular, the spread of diseases and pests, also proved to be important factors leading to a decrease in the hardiness of dark coniferous forests. Measures to regulate the impact of anthropic factors, such as unstable forest management and insufficient environmental protection, are becoming

extremely important for preserving biodiversity and ensuring the stability of dark coniferous forest ecosystems.

Predictors or factors of “primary” influence include abiotic abnormalities (climate aridisation, exposure to ultraviolet radiation and stratospheric ozone, and anthropic pressure (anthropogenic air pollution and forestry activities that lead to changes in the species composition of stands (Meshkova *et al.*, 2018; Hůnová *et al.*, 2019). Phytocenotic prerequisites for the dieback of *Abies alba* Mill. in Forest cenoses, which were considered in the paper by M.I. Soroka *et al.* (2019), involve complex interactions between different plant species and environmental factors. Propensity of *Abies alba* Mill. to drying time is determined by the composition and structure of the surrounding vegetation, soil characteristics and climatic

conditions in specific cenoses of Kutske forestry. Understanding these phytocenotic dynamics is essential for implementing effective conservation and management strategies to overcome the challenges of *Abies alba* Mill. drying out in this forest enterprise.

According to R.C. Cobb & M.R. Metz (2017) biotic factors are considered to be secondary, reinforcing the role of previous ones and leading to irreversible changes in forest ecosystems. They noted that the spread of pathogens in forest ecosystems not only causes diseases, but also contributes to interaction with various disorders, such as insect pests and extreme weather conditions. The relationship between tree diseases and forest disturbances creates feedback, where the presence of one element increases the likelihood and severity of the other, leading to a complex cycle for forest health and sustainability. I.N. Pavlov *et al.* (2020) found that the impact of invasive pest species is recognised as the most significant on the planet's dark coniferous forests – *Polygraphus proximus* Blandford and *Ips typographus* Linnaeus, which cause mass tree death and alter the composition, structure, and function of forests. J.L. Morris *et al.* (2018) described that bark beetles become influential agents of change in socio-ecological systems, significantly affecting forest ecosystems. Their attacks, often caused by environmental stressors, can lead to widespread tree mortality, altering the composition and structure of forests. The impact of bark beetle activities extends far beyond environmental changes, affecting forest-dependent economic activities and challenging established forest-related social dynamics. According to forecasts, prolonged warming during the 21st century will contribute to the mass development of bark beetle populations in ecosystems where they were previously limited by climatic conditions (Robbins *et al.*, 2020). Therefore, despite the high natural resistance of fir and fir-beech forests compared to pure spruce forests to

most adverse environmental factors (Zhang *et al.*, 2018; Lukashchuk *et al.*, 2023), a detailed study of pathologies of biotic origin is the basis for developing a strategy for forest conservation and biodiversity maintenance. I.M. Kulbanska *et al.* (2022) considered that increased resistance of fir and fir-beech stands may occur due to allelopathic effects, for example, *Fagus sylvatica*. At the same time, a decrease in the proportion of deciduous tree species in the fir forest stand that are not infected with the same types of diseases as fir can contribute to a general decrease in the resistance of the stand to the occurrence of infectious epiphytotics.

Thus, despite the fact that the species composition of potential predictors of the influence of biotic origin on the condition of white fir is more or less outlined, some issues, in particular, regarding the substantiation of the names of diseases, aetiology, features of symptoms with simultaneous exposure to different species, have not yet been considered. Therefore, the purpose of this study is to determine the signs, spread, and effect of ulcerative tumour-like disease factor on the branches and trunks of white fir.

Materials and Methods

Field studies of the symptoms and spread of ulcerative tumour-like disease on shoots and trunks of white fir were conducted during the growing season of 2023 on the territory of forest plantations of the Pokuttia Carpathians within the forest fund of the Kutske forestry branch of the State Specialised Enterprise “Forests of Ukraine”. Two trial plots were established, which differ in the main silvicultural and inventory indicators, but fully represent the typical conditions of the study area.

Trial area No. 1 was established in block 23, stratum 13 of the Kosivske forestry. The height above sea level is 540 m, the slope is 25°. The total area of the compartment – 0.3 hectares. Forest stand composition – 90% fir 10% spruce + beech. Age – 93 years. Average height – 28.0 m,

average diameter – 40.0 cm, density – 0.50, reserve – 460 m³×ha⁻¹. Quality index – I. The forest type – fresh fir mixed beech forest (-).

Trial area No. 2 is established in block 31, stratum 9 of the Kosiv forestry. The height above sea level is 790 m, the slope is 36°. The total area of the compartment – 11.5 hectares. Forest stand composition – 70% fir 20% spruce 10% beech. Age – 103 years. Average height – 25.0 m, average diameter – 36.0 cm, density – 0.40, reserve – 300 m³×ha⁻¹. Bonitet – II. The forest type is wet beech mixed fir forest (-). The silvicultural and taxation characteristics of the trial areas are given according to the taxation descriptions of the enterprises provided by the Ukrderzhlisproekt production association. In total, 214 specimens of white fir were registered within the test areas, classified as undergrowth. To assess the prevalence and harmfulness of the disease, the degree of thickness, not the age of woody plants, was taken into account. This is conditioned by the fact that the undergrowth (even within the same height) has a different (sometimes by decades) age, which is the norm for white fir and reflects its high shade tolerance, and the ability to wait for a long time for a free “window” in the stand.

Special macroscopic, microscopic, and mycological research methods were used to determine the species composition of infectious disease pathogens. Identification of the collected phytopathological material was carried out directly using light microscopy methods in the Educational and Scientific Laboratory of Biotechnology and Cellular Engineering of the National University of Life and Environmental Sciences of Ukraine.

Based on a detailed analysis of the ulcerative tumour-like disease of white fir, certain features in the symptoms of the pathological process were determined, in particular, two types of lesions were identified. Type 1 (usually characteristic of fir undergrowth) is characterised by the development of more or less extensive

(sometimes up to 15-20 cm) muff-like tumours encircling the trunk (shoot). Such tumours from the moment of development have a surface with longitudinal and transverse cracks, which is generally uncharacteristic for fir of any age.

Over time, some tumours of this type develop stepped ulcers, most often near knots on the trunks. Type 2 (typical for plants of older age groups and trees of the upper tiers) is characterised by the development of muff-like tumours, the edges of which are not clearly defined, often without changing the structure of the bark (longitudinal and transverse cracks, characteristic of type 1 lesions, do not develop). However, a characteristic transverse ulcer (deep crack) is formed, which in symptoms resembles an open form of transverse oak cancer with a similar effect on the physiological state of the plant. That is why even in the reporting materials of forestry enterprises, this disease is called “transverse cancer” of fir.

To establish the morphometric parameters of witches’ brooms, the length of shoots and needles was measured, and the number of needles, lateral buds of regular branching and lateral axillary buds was calculated. Latin names of higher plant species are given based on: World Flora Online (n.d.), mycobiotes – based on: Index Fungorum (n.d.). The degree of damage to trees was determined by condition categories (Resolution of the Cabinet of Ministers of Ukraine No. 756, 2016). Calculations and statistical processing of data were carried out using Microsoft Excel software suite. The research was conducted in compliance with the standards specified in the Convention on Biological Diversity (1992) and the Convention on the Trade in Endangered Species of Wild Fauna and Flora (1973).

Results

The causative agent of ulcerative tumour-like disease of white fir is a diverse fungus with a complete development cycle *Melampsorella*

caryophyllacearum J. Schröt. (outdated name – *Melampsorella cerastii*, synonym – *Melampsorella elatina* (Alb. & Schwein.) Arthur 1907) (Scholler *et al.*, 2022). Spermogonia on the upper surface of the needles between the epidermis and cuticle, yellow to honey-yellow, dotted, 100-120×30-50 µm in size, clearly protruding from the epidermis. Aecium on the lower surface of needles in the form of yellowish stripes located along the central vein. Aeciospores are ellipsoid or angular, with pink-orange contents, 15-20×18-20 µm; the shell is colourless, warty, 1-2 µm thick. Uredinium mainly on the underside of the needles, small, rounded, 0.1–0.5 mm in diameter, yellow, formed directly in the stomata. Uredospores are ellipsoid or almost spherical, 15-30×14-24 µm, with yellow-orange contents; the shell is colourless, bristly. Telium on the underside of the leaves develops more or less whitish or ochreous-yellow spots. Teleospores are grouped in the cells of the epidermis, spherical, ellipsoid or angular, irregular, 15-25 µm in diameter, with colourless or yellowish contents; the shell is colourless, smooth, 1 µm thick. Spermogonial (0) and aecial (I) stages of pathogen development occur on needles of *Abies alba* Mill., and urediniostadia (II) and teliostadia (III) develop on plants from the Clove family (*Caryophyllaceae*), in particular, on common starwort (*Stellaria graminea* L.) and greater starwort (*S. holostea* L.), water chickweed (*S. aquatica* Scop.), species of the genus *Cerastium* (*Cerastium* L.) and others. Currently, it is known that the endemic Turkish fir species *Abies nordmanniana* subsp. *equi-trojani* (Asch. & Sint. ex. Boiss.) Coode & Cullen is also sensitive to this pathogen (Keleş *et al.*, 2021).

The first symptoms of the lesion appear on young branches and shoots, on which muff-like thickenings develop (Fig. 1). Next spring, a witches' broom sprouts vertically from the buds of infected shoots in the places where tumours form, which has the appearance of a cluster of dense shortened shoots with short yellow-green

needles (Fig. 2). Starting from mid-summer, the needles of witches' brooms develop aecial sporulation, which has the appearance of orange or yellowish cylindrical pustules filled with aeciospores. Aecias develop on the underside of needles, along the middle vein. The affected needles eventually completely fall off. In the following years of pathology development, new shoots appear on the witches' brooms, and new aecia develop on them. Usually, several bushes of witches' brooms with a diameter of up to 60 cm, and sometimes more, appear at the crown of the tree. The life cycle of witches' broom can last for 20 years or more. Very rarely (within the statistical margin of error), a witches' broom with perennial needles was found, which is not characteristic of the ulcerative tumour disease of white fir. Obviously, such witches' brooms have a different origin, which requires further study.



Figure 1. Muff-like thickenings – initial stage of pathogenesis of ulcerative tumour-like disease of white fir

Source: photo by the authors



Figure 2. The development of witches' brooms in the crown of white fir trees is a typical symptomatic sign of *Melampsorella caryophyllacearum* infection

Source: photo by the authors

On the affected trunks, a closed-type thickening with longitudinal surface cracks is formed. Over time, the crust cracks and falls off, partially exposing an open stepped ulcer (Fig. 3). Growths can appear along the entire length of the trunk, often several at once. From the affected shoots, the mycelium of the pathogen penetrates directly into the tree trunk, where it causes the process of necrotisation of the cambial layer, as a result of which atypical thickenings form on the trunk, usually covered with a crust with longitudinal and transverse cracks. On the affected shoots, yellowish needles appear locally, intensively crumbling. Over time, the crust cracks, partially falls off, exposing an open step wound, cracks on the surface of which begin to deepen. Growths are formed along the entire length of the tree trunk. Affected white

fir trees can show signs of weakening for several decades. The condition of infected woody plants significantly depends on the location of ulcerative tumour lesions on the trunk. The most dangerous lesions are those that develop in the sub-crown part of the trunk, leading to its dieback.



Figure 3. Cancerous and ulcerative wounds of various types of white fir

Note: a – on shoots; b, c – on trunks

Source: photo by the authors

The disease causes weakening and dieback of white fir, especially undergrowth, reduces the yield of commercial wood, contributes to the infection with rot pathogens, in particular, *Phellinus hartigii* (Allesch. & Schnabl.) Pat. and the development of foci of stem pests. As evidenced by the studies, quite often the fir undergrowth is significantly weakened and dieback if there are only closed tumours on the trunk without exposing the wood (without ulceration). Trees of older age groups mainly develop ulcers (common or stepped) located across the trunk.

Based on a detailed analysis of the ulcerative tumour-like disease of white fir, certain features in the symptoms of the pathological process were determined, in particular, two types of lesions were identified. Type 1 (usually characteristic of fir undergrowth) is characterised by the development of more or less extensive (sometimes up to 15-20 cm) muff-like tumours encircling the trunk (shoot). Such tumours from the moment of development have a surface with longitudinal and transverse cracks, which is generally uncharacteristic for fir of any age. Over time, some tumours of this

type develop stepped ulcers, most often near knots on the trunks. Type 2 (typical for plants of older age groups and trees of the upper tiers) is characterised by the development of muff-like tumours, the edges of which are not clearly defined, often without changing the structure of the bark (longitudinal and transverse cracks, characteristic of type 1 lesions, do not develop). However, a characteristic transverse ulcer (deep crack) is formed, which in symptoms resembles an open form of transverse oak cancer with a similar effect on the physiological state of the plant. Perhaps that is why, even in the reporting materials of forestry enterprises, this disease is called "transverse fir cancer".

Accounting data on the spread of ulcerative tumour-like disease on the undergrowth and trees of white fir of the upper tiers of the stand with a division into degrees of thickness and types of lesions (1 and 2) indicate the superiority of type 1 of lesions in young white fir trees (Table 1). The table does not consider dead white fir trees of various degrees of thickness that did not have symptoms of ulcerative tumour-like damage.

Table 1. Spread of ulcerative tumour-like disease on the undergrowth and trees of white fir of the upper tiers

Degree of thickness, cm	Total recorded trees, units	Including infected trees, units	Number of ulcerative tumour-like lesions by type				Total lesions, units	Spread of the disease, %
			Type 1		Type 2			
			units	%	units	%		
Undergrowth								
2	62	43	84	81.6	19	18.4	103	69.4
4	49	24	46	88.5	6	11.5	52	49.0
6	43	10	20	71.4	8	28.6	28	23.3
8	31	12	7	63.6	4	36.4	11	38.7
10	18	3	4	66.7	2	33.3	6	16.7
12	11	1	2	66.7	1	33.3	3	9.1
Total	214	93	163	-	40	-	203	-
Upper tier trees								
28	26	1	0	0.0	1	100.0	1	3.8
32	71	3	0	0.0	3	100.0	3	4.2
36	119	4	1	20.0	4	80.0	5	3.4
40	186	15	3	15.8	16	84.2	19	8.1

Table 1, Continued

Degree of thickness, cm	Total recorded trees, units	Including infected trees, units	Number of ulcerative tumour-like lesions by type				Total lesions, units	Spread of the disease, %
			Type 1		Type 2			
			units	%	units	%		
Upper tier trees								
44	18	2	0	0.0	2	100.0	2	11.1
48	6	4	0	0.0	4	100.0	4	66.7
52	7	1	0	0.0	1	100.0	1	14.3
56	3	1	0	0.0	1	100.0	1	33.3
Total	436	31	4	-	32	-	36	-

Note: affected plants include undergrowth that had both symptoms of type 1 and 2 lesions, and witches' brooms. There were often plants whose only visual sign of infection was witches' broom; type 1 tumour-like growths (without ulcers) and type 2 – ulcerative tumour-like (stepped for undergrowth and young plants) and transverse (for trees of the upper tiers)

Source: compiled by the authors

Notably, there is no correlation between the height of the undergrowth and its age – to a greater extent, this depends on stressful (depressing) factors for plants. It is established that the average distribution rate of ulcerative tumour-like disease is equal to 43.5% on the undergrowth. The largest number of fir specimens with typical visible signs of infection is attributed to the smallest degrees of thickness. Accordingly, the total number of lesions (totaling type 1 and type 2) was also highest on trees with 2 and 4 cm thicknesses. Note that the type of ulcerative tumour disease lesion also prevailed in the undergrowth, that is, tumour-like formations on shoots and trunks without ulcers. At the same time, the disease is found not only on trunks, but also on shoots. The affected young undergrowth is usually depressed, and a significant percentage of plants are dead.

The report also covers 436 specimens of white fir of the upper tiers. The average spread of ulcerative tumour-like disease is 7.1%. The largest number of fir specimens with typical visible signs of infection is attributed to average (36–44 cm) degrees of thickness. The total number of lesions (total type 1 and type 2) was the highest on trees of 40 cm thickness (this

trend can be explained by the fact that in the studied plantings, the most common were trees that reached 40 cm in diameter). Note that on trees of older age groups, type 2 of ulcerative tumour-like disease prevailed, that is, there are ulcerative tumor-like and transverse growths (inflows). It is known that any ulcers (inflows, tumours) weaken the plant, but its death (due to the objective characteristics of obligate pathogens, in particular, the causative agent of ulcerative tumour-like disease of fir) is quite rare. This happens if more than 2/3 of the trunk is ringed and more than its perimeter. Such trees are mainly windbreak due to the defeat of their pathogens by stem rot, most often on fir it is Hartig's white trunk rot, which affects the tree with the core exposed and causes core corrosion rot.

In addition, a typical sign of ulcerative tumour-like disease of white fir is the presence of pathologies such as witches' broom, which occurs due to excessive bud formation. The needles on witches' brooms are shorter and wider compared to healthy needles and fall off annually during August and September. It is established that in the crown, the witches' broom is formed exclusively on the side branches, closer

to the top of the shoot. Visually, on the examined specimens of undergrowth, and on trees of older age groups, including model trees of 60-80 years of age, which were selected by us for

other studies (in particular, tracheid pathology of white fir), witches' brooms were registered in the crown, which differed in morphometric indicators (Table 2).

Table 2. Morphometric parameters of shoots on the witches' broom of white fir

Shoot branching order	Indicator							
	Shoot length, mm		Buds of regular branching, units		Double shoot, units/ 10 mm shoot		Axillary buds, units	
	WBS	NS	WBS	NS	WBS	NS	WBS	NS
3	42.4±2.1	50.9±3.7	3.2±0.2	2.4±0.2	17.1±0.5	14.6±1.5	9.4±0.8	1.6±0.4
4	31.5±1.2	27.8±2.4	2.2±0.1	0.7±0.1	14.3±0.2	16.9±1.4	8.0±0.2	1.0±0.1
5	32.4±1.0	18.5±1.3	1.6±0.1	0.1±0.03	13.7±0.2	18.1±0.8	7.2±0.1	0.05
6	25.1±0.4	-	1.0±0.1	-	13.4±0.1	-	3.6±0.1	-
7	15.2±0.4	-	0	-	9.5±0.1	-	1.4±0.1	-

Note: WBS – witches' broom shoot, NS – normal shoot (control); 3-7 branching order, + sign means that this feature in shoots of the same branching order of the witches' broom and control has statistically significant errors (at $P < 0.05$)

Source: compiled by the authors

In 5 years, a system of branches consisting of five orders is developed from a lateral bud on the second order axis of branching of the witches' broom shoot, while a normally developed shoot forms only three orders of branching.

In length, the shoots of the witches' broom of the third order are smaller than normal, but they develop significantly more buds of regular branching and axillary buds, half of which will develop secondary shoots next year. Shoots of the fourth order of the witches' broom are longer than normal shoots, but they develop almost three times as many shoots of regular branching and 8 times as many axillary buds, about 30% of which will germinate next year. Shoots of the fourth order of branching developed from axillary buds are 20-25% shorter than shoots of regular branching, their growth characteristics depend on the location on the shoot: longer ones are formed from axillary buds developed in the upper half of the shoot, and short ones – in the lower part. On normal shoots of the fourth order, only 1-2 axillary buds develop, and they remain dormant. Witches'

broom shoots of the fifth order of branching are much longer and develop 16 times more lateral buds than normal shoots, approximately 90% of the shoots of which do not develop buds of regular branching at all. Axillary buds on normal shoots of the fifth order of branching are not developed, in the shoots of the witches' broom they continue to develop in large numbers. Shoots of the sixth and seventh orders of branching are not formed on normal shoots, and more than 60% of all axes are formed in the shoots of the witches' broom on these orders. Normal shoots and witches' broom have different orientation in space: normal ones are characterised by plagiotropic (perpendicular to the axis of the tree trunk and parallel to the plane of the Earth) arrangement of shoots, shoots of witches' broom grow orthotropically (parallel to the axis of the trunk or at an acute angle to it). The above results show that the shoots of the witches' broom differ from the shoots of the normal part of the crown. This information indicates significant differences in the morphometric parameters of normal fir shoots and

shoots on which the witches' broom was developed. The main difference is the abundant branching, due to which a denser fragment of the crown is formed, which is visually easily detected. There was also a dead white fir tree with no signs of ulcerative tumour disease (bacterial wetwood (causative agent – *Lelliottia nimipressuralis* (Carter 1945) and burn-type diseases).

A. Goychuk *et al.* (2022) described that the overall sanitary condition of dark coniferous forests forms a close correlation between biotic predictors and abiotic factors. Currently, the phytopathogenic bacterium *Lelliottia nimipressuralis* (Carter 1945) (Brady *et al.*, 2013) is a major contributor to the general pathology of white fir, characterised by its dynamic spread within the range of forests with white fir and causing massive mortality of trees of different age groups. I. Kulbanska *et al.* (2022) investigated that the main symptoms of infection of fir trees with bacterial droopy include the development of cracks and ulcers on shoots and trunks, detachment of the rhytidome, abundant exudate discharge, exposure of the primary bark and phloem, trees form a typical “hedgehog-like” appearance due to the mass development of water shoots. These results highlight the importance of studying and understanding the complex of symptoms for early diagnosis and effective control of this bacterial disease. According to A. Madmony *et al.* (2018), causes of weakening and death of trees of the genus *Picea* are fungi of the genus *Fusarium* sp. and the species *Heterobasidion parviporum* Niemelä & Korhonen, which cause root rot of varying intensity. Their study aimed to understand how these environmental factors affect the production of monoterpenes, which are important secondary metabolites in plant defence mechanisms. The revealed differences in monoterpene responses in the two clones reveal a complex interaction between drought stress and fungal infection in the formation of

chemical defence mechanisms of Norwegian spruce. Reports of massive outbreaks of these phytopathogens have been confirmed by researchers from different countries.

Researchers from Finland M.M. Müller *et al.* (2018) conducted extensive surveys to map the geographical distribution of infection *Heterobasidion*, identifying key factors that affect its distribution, such as climatic conditions, tree species composition, and forest management. These studies provide valuable information on the spatial patterns of *Heterobasidion* root rot, helping forest managers to implement targeted disease management strategies and sustainable forest practices in northern Finland. According to the data of Polish researchers P. Lech *et al.* (2020), damage to white fir and Scots pine trees in the forests of Central Europe caused by the massive spread of *Viscum album* L., which was monitored during 2008–2018. Systematic surveys were conducted to assess the prevalence and distribution of infestations on various tree species in Poland's forest ecosystems. The results of this study provide valuable information on time patterns and factors influencing the spread of European mistletoe, which is essential information for forest management practices and strategies aimed at reducing the impact of mistletoe on tree health and overall forest ecology in Poland. The pathogenic impact on white fir seedlings in forest nurseries by the fungus *Phytophthora abietivora* was considered by D.W. Li *et al.* (2019). The discovery of *Phytophthora abietivora* on fir trees in Connecticut highlights the need for vigilance in monitoring and managing emerging threats to tree health in the region. However, the least attention of researchers is paid to the disease, which is known as “fir cancer”, “fir broom rust”, etc. Only some results of studies of rust fungi of the order Pucciniales are known, in particular, *Melampsorella caryophyllacearum* J. Schröter (Keleş *et al.*, 2021), which cause the witches'

broom pathology on white fir trees. The findings revealed how the fungus, which causes powdery mildew, affects visual and internal features of *Abies nordmanniana* subsp. *equi-trojani*, providing valuable information about the ecological interactions between the pathogen and the host tree. To understand a particular plant pathology, well-established types of diseases are usually used, which are based solely on symptoms, that is, on anatomical and morphological features. When determining the types of diseases, the causes of their occurrence are usually not considered. In particular, there is a clear definition and understanding of “ulcers” as a type of disease – infectious or non-infectious, that is, depressions on plant organs (usually trunks) surrounded by living tissue (small ulcers are called anthracnose). Various thickenings, growths, in particular muff-like ones, have the common name “tumours” (this type of disease has a different nature of origin, in fact, and like other types of diseases). As for the term “cancer” (as a type of disease), it is usually not distinguished among plant diseases as a separate type of disease. Although now the term “cancer” defines diseases (types of diseases) that are characterised by the development of tumours (growths), ulcers, difficult-to-heal or non-healing wounds (often with the release of oleoresin, exudate, etc.). All these names (ulcer, tumour, growth, etc.) are different types of diseases that do not allow adequately understanding the symptoms of a particular pathology. In any case, if necessary and to preserve the established names of diseases, in terms such as “cancer ulcers” (these are different types of diseases), the word “cancer” should be put in quotation marks. In terms of symptoms, the disease under study most closely corresponds to the name “ulcerative tumour-like disease”, since in the initial stages of the disease, a tumour (growth) is developed first and over time, a common, but more often a stepped ulcer is formed.

Conclusions

Based on the study of the current sanitary condition of *Abies alba* Mill. trees growing in the Pokuttia Carpathians, typical symptomatic signs of the ulcerative tumour disease of plants of different age groups were recorded and identified. The causative agent is an obligate phytopathogen *Melampsorella cerastii* Wint. (= *Melampsorella caryophyllacearum* J. Schröt.). This pathology in the scientific and educational literature is associated with outdated names – “fir cancer”, “rusty fir cancer”, “transverse fir cancer”, “stepped fir cancer”, etc., which are based solely on anatomical and morphological features and do not consider the aetiology. The main symptoms of the pathogenesis of ulcerative tumour-like disease of white fir are the formation of typical muff-like growths on young branches and shoots, and witches’ brooms. There are two types of course of this disease, in particular, the type manifests itself in the form of muff-like thickenings and is characteristic mainly for the growth of fir. In Type 2 of the disease, deep transverse ulcers with cracks are formed. Ulcerative tumour-like disease of white fir is widespread in the forests of the Pokuttia Carpathians, the average spread rate is 43.5% on undergrowth and 7.1% on trees of older age groups. The development of this pathology leads to a general weakening of white fir trees, which makes them sensitive (susceptible) to other environmental factors.

Given the significant spread of ulcerative tumour-like disease of white fir, which tends to increase, further research should be aimed at reducing the infectious background in stands with the participation of white fir in the territory of the Pokuttia Carpathians. For this purpose, the disease should be detected first of all on the undergrowth in fir forests. Trees with signs of ulcerative tumour-like disease (development of tumours, witches’ brooms, ulcers) must be removed from the stand and

then disposed of. The same applies to white fir trees at the stage of lightening, thinning and clearing – trees with symptoms of damage should be removed. Special attention should be paid not only to the affected trunks, but also to the affected lateral branches of young trees, as the primary infection occurs through the needles and then spreads throughout the plant. It should also be borne in mind that the causative

agent, like other obligate pathogens, stimulates plant growth and development in the initial stages of pathology.

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None.

Conflict of Interest

None.

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Виразково-пухлиноподібна хвороба ялиці білої в деревостанах Покутських Карпат

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Анотація. Сучасний стан темнохвойних лісів Землі є біоіндикатором глобальних змін навколишнього середовища, зокрема процесу поступової деградації деревних видів родів Сосна, Ялина та Ялиця, обумовленого негативним впливом антропогенної діяльності, абіотичних та біотичних чинників. Метою дослідження є встановлення симптоматики, поширеності та шкодочинності збудника виразково-пухлиноподібної хвороби на пагонах і стовбурах ялиці білої. Дослідження проводили на території лісового фонду Покутських Карпат, зокрема у межах філії «Кутське лісове господарство» Державного спеціалізованого господарського підприємства «Ліси України» у Косівському лісництві. У роботі використано класичні фітопатологічні та мікологічні методи, за допомогою яких досліджено етіологію захворювання, аналіз типової симптоматики (починаючи з ранніх етапів), проведено мікроскопію уражених частин ялиці. Досліджено симптоматику, етіологію та патогенез виразково-пухлиноподібної хвороби ялиці білої, яка має тенденцію до поширення. Обґрунтовано нову назву хвороби, зокрема пропонується використовувати замість вживаної назви «рак» ялиці – «виразково-пухлиноподібна хвороба» ялиці. Показано, що типовою ознакою інфікування є формування пухлин, які з часом трансформуються у виразки. Встановлено, що на підрослі ялиці переважає пухлиноподібний тип ураження, а на рослинах

верхніх ярусів – виразковий. Зазначається, що типовою ознакою виразково-пухлиноподібної хвороби ялиці білої також є наявність патологій типу «відьмина мітла». Пропонується для зменшення інфекційного фону видаляти уражені дерева із типовими ознаками інфікування виразково-пухлиновидної хвороби, особливо при освітленнях і прочистках, оскільки уражені дерева від інфекції не звільняються. Таким чином, оцінка ризику, спричиненого інфікуванням дерев ялиці білої виразково-пухлиновидною хворобою на рівні конкретних деревостанів, і забезпечення належної реакції на потенційні ризики зараження є важливою частиною сталого управління лісами

Ключові слова: *Abies alba*; іржасті гриби; біотичні чинники; симптоматика; етіологія; патогенез

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The influence of agroforestry on the formation of the structure of forest ecosystems

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Abstract. The functional load of forests necessitates the activation of meliorative measures to optimize the functioning of agrolandscape complexes. These measures contribute to improving the environmental situation and advancing towards sustainable functioning of forest ecosystems. Therefore, the study of the structural and species formation of forest ecosystems is of significant scientific interest. The aim of the article was to analyse the impact of agroforestry measures on the process of forming the structure of forest ecosystems through a comprehensive examination of interrelationships. The research utilized general scientific methods, including specification, deduction, systemic analysis, synthesis, and abstraction, as well as formalization. During the study, vectors of organizing optimized systems of protective forest plantations were analysed, and environmental protection priorities for the development of agroforestry ecosystems were substantiated. Basic principles of managing the agroforestry complex based on sustainable land use were identified, including a comprehensive approach, ecologization of the process, and continuous monitoring. The study revealed current ecological consequences of irrational melioration for forest plantations, such as increased erosion processes and land resource degradation. Risks and challenges requiring preventive solutions were identified. It was proven that increasing the share of agroforestry plantations would allow optimizing the environmental situation in Ukraine, promoting the regeneration of the natural resource base, restoring landscapes, and minimizing land resource degradation processes. The article proposed key measures to optimize the environmental situation at the local level of forest ecosystems, as well as preventive measures to prevent destructive impacts, including the improvement of legal support and the implementation of strict measures of responsibility for irrational resource use. The value of the conclusions lies in their practical application for monitoring the state and the process of forming the structure of forest ecosystems under the influence of agroforestry measures. They also contribute to the effective development of preventive and regenerative protective measures and the formation of balanced forest ecosystems

Keywords: protective plantations; erosion processes; monitoring; zoning; potential risks; assortment of woody plants

Introduction

The actualization of environmental issues in the functioning of modern agrolandscapes is primarily attributed to the irrational use of land, which does not ensure adherence to optimal ecological parameters for territory functioning. Protective forest plantations (PFPs) are positioned as a fundamental component of agroforestry ecosystems and, therefore, require proper attention to the identification and implementation of landscape-ecological principles in their formation. The system of measures for forest melioration in agrolandscape complexes should ensure the optimization of

the regional environmental situation while simultaneously guaranteeing the development towards sustainable agricultural functioning. It can be argued that the agroforestry complex operating in Ukraine is identified as insufficiently effective. According to official data, soil erosion phenomena lead to significant annual losses amounting to 9 billion UAH (Furdychko & Tymochko, 2020).

The issues of agroforestry and its correlation with the structural features of forest plantations have become the subject of scientific research by several Ukrainian scientists. Some

experts argue that forestry should be identified as part of a large multifunctional system of comprehensive natural resource use and reproduction, requiring the application of a principle of comprehensive research (Skliar *et al.*, 2019). For instance, the position of I. Koval (2023) convincingly illustrates the inefficiency of organizing forestry management, leading to the irrational use of natural and economic resources, lack of investments, and loss of development prospects. At the same time, S.M. Abu Dib (2022) advocates for the need to update an innovative position for adjusting the species composition of forest ecosystems based on the principles of sustainable resource use, landscape preservation, and mitigation of destructive consequences of excessive anthropogenic pressure.

Recent works by researchers S. Amons & O. Krasnyak (2023) emphasize that systems of special protective forest plantations have a significantly more positive impact on the ecological condition in agroecosystems compared to individually formed forest belts. H.I. Kravchuk & A.I. Hutsol (2019) consider the conceptual principles of optimizing PFP systems in agrolandscape complexes, focusing on increasing the quantitative and qualitative indicators of protective forest cover on agricultural territories, which will significantly enhance the ecological functionality of PFPs.

Ukrainian scientists O.A. Bida *et al.* (2022) argue for the urgent need for institutional changes and adaptation of the existing regulatory framework to current sustainable development requirements. According to these scientists, implementing such conceptual prerequisites will ensure the optimization of forest ecosystem areas based on a functional-zonal principle and become an ecological foundation for further sustainable development of agrolandscapes. Researchers O. Savchuk & A. Liubchych (2019) highlight aspects of

compliance between the application of the resource potential of forest plantations and their extended regeneration. They see the introduction of an integrated forest management system as a priority. According to them, it is necessary to designate protected areas of a known area where ecological processes can occur naturally without being restricted by anthropogenic factors. At the same time, scientists propose transforming the forestry sector, prioritizing the satisfaction of the needs of the natural environment in areas related to agrolandscapes.

Most Ukrainian scientists agree on the priority of issues related to protecting agrolandscapes from pollution and degradation, the need to preserve biodiversity, and the formation of an ecological basis for forestry. Despite the significant contributions of researchers to the field of scientific research in this study, there is a limitation in exploring the possibilities of restructuring the structure of forest plantations within agroforestry complexes. The purpose of this research is a detailed analysis of the vectors of mutual influence between the agroforestry system and the structural formation of forest ecosystems, with the identification of priority directions for regenerative and preventive measures.

Materials and Methods

During this scientific research, a combination of general scientific methods was applied. The theoretical foundation was laid by contemporary relevant scientific works, sectoral Ukrainian and foreign literary sources, publications in specialized journals, monographs, materials from scientific conferences, regulatory documents, statistical information, and practical results related to optimizing the agroforestry system.

The scientific methodological basis of the study was built on the principles of comprehensive and systematic approaches to the analysis

of agroforestry measures and their systems as multi-vector formations in the functioning of forest and agrolandscape ecosystems. This approach allowed for the identification of conceptual principles within a comprehensive methodology for researching the optimization of forest plantations within agrolandscape complexes, based on landscape-ecological differentiation. The abstraction method was employed in the research process to identify basic categorical concepts and form a concept of the integrated process of the agroforestry system as a structurally consequential set of relationships. The abstract-logical method was applied to individualize the conceptual apparatus in the research field, form theoretical generalizations, and draw conclusions. Additionally, the method of transitioning from abstract to concrete was utilized, sequentially implementing general theoretical information on the impact of agroforestry measures on the formation of forest ecosystems structure into specific vector analysis of activities in the investigated field in Ukraine.

Synthesis and system analysis methods were involved in the research process to extract the essence of the functionality of the study object, identify priority strategic directions for optimizing agroforestry in Ukraine, primarily in terms of its impact on the formation of forest ecosystems. Furthermore, through analytical processing of information arrays, the research identified characteristic features of mutual influence among components of the agroforestry system, highlighting priority indicators of mutual influence and prospective development directions for improving the existing situation. The effectiveness assessment of the agroforestry measures system aimed at stabilizing ecosystems was realized using the method of system analysis.

The specification method was employed during the research to document the significance and effectiveness of the management-

functional system for local agroforestry complexes. Using the specification method, the assortment of tree and shrub species for protective forest plantations based on landscape-typological criteria was justified, along with outlining optimal conditions and effective solutions for the preservation and regeneration of agrolandscapes and forest plantations, while simultaneously mitigating risks to the natural environment through preventive measures.

The comparison method was used to identify the specifics of the development of agroforestry systems in Ukraine based on indicators of quantitative and qualitative dynamics. The inductive method was applied for effective predictive analysis of characteristic features of the agroforestry system's functioning in Ukraine. The deductive method was utilized to record practical proposals for improving the national management system for agro-amelioration and afforestation.

To document priority directions for prospective optimization of the national agroforestry system in accordance with the principles of sustainable natural resource use, the formalization method was applied. Moreover, through the functionality of this method, the significance of anthropogenic impact for the effective functioning and stability of agrolandscapes was emphasized. The study established the limits of transformative processes in the agroforestry system, forming conclusions for future practical implementation in the scientific-practical transformation system for managing agroforestry complexes. Throughout the research, the provisions of the Convention on Biological Diversity (1992) were adhered to.

Results

The most influential structural element of the phytomeliorative system is identified as the engineering-protective vector of activity, focusing on the formation of specific plantations

aimed at protecting landscapes from erosion processes. Agroforestry, primarily, involves the creation of protective forest plantations, most commonly represented in the form of field protection forest strips (FPFS) and their systems (Mishenin *et al.*, 2021a). The main conceptual direction of agroforestry measures is the optimization of conditions for the development of agricultural crops to increase their productivity. It is worth noting that the system of forming protective forest plantations significantly affects the structure of forest ecosystems.

The interdependence of indicators of age and species structure of the forest ecosystem and agroforestry measures is primarily actualized by inefficient land use and non-compliance with optimal landscape functional parameters. The primary practical function of linear-type PFPs should be the formation of an ecological framework for the agrolandscape (Abu Dib, 2022). However, as of today, their quantitative and qualitative condition does not meet minimum requirements that could ensure proper functionality. In Ukraine, there is an unbalanced ratio of agricultural land to forests, deterioration of the functional state of PFPs, minimization of their area, and weakening of protective and meliorative functions. An important problem is the inefficiency of the construction of protective plantations, significantly reducing their agromeliorative functionality.

Overall, the destruction of the protective function of agrolandscapes through PFPs in Ukraine, as well as the improper structural-functional state of forest ecosystems, is due to a significant slowdown in the process of creating new plantations and worsening their forestry condition, disrupting their structure. Intensive erosion phenomena and prolonged droughts, caused by climate change, are not compensated by existing systems of linear protective forest plantations, which protect only

30% of agrolandscapes (Kravchuk & Hutsol, 2019). The situation is complicated by the elimination of agroforestry services, the minimization of stimulating innovative innovations, and the lack of proper legal support and strict responsibility for irrational land use. Protective forest plantations form the ecological basis for the effective functioning of agrolandscapes, but their shortage and inadequate qualitative condition do not meet current needs.

The optimal structure of PFPs by species components significantly influences the indicators of agroforestry efficiency in different regions of Ukraine. Conversely, meliorative measures significantly affect the formation of the structure of forest ecosystems (Abu Dib, 2022; Savchuk & Liubchych, 2019). Optimal placement of PFPs within agroforestry ecosystems, correct composition of tree species structure, identification of destruction factors, involvement of innovative technological and managerial solutions can synergistically provide the highest ecological effect of agroforestry, including the process of forming the structure of forest ecosystems.

Protective forest plantations, essentially cultural biocoenoses, are characterized by uniform spatial distribution. Regarding vertical structure, four main layers are distinguished (crown, shrub, herbaceous, and ground layers) (State Agency of Forest..., 2020; Amons & Krasnyak, 2023). FPFS, in this context, perform water protection, soil protection, and climate-regulating functions. Today, these protective forests differ in age, structure, and species composition. In Ukraine, among the species structure, red oak (*Quercus rubra*), American ash (*Fraxinus americana* L.), small-leaved lime (*Tilia cordata* Mill.), field maple (*Acer campestre* L.), green ash (*Fraxinus lanceolata* Borkh.), and black locust (*Robinia pseudoacacia* L.) are most commonly found (Fig. 1).

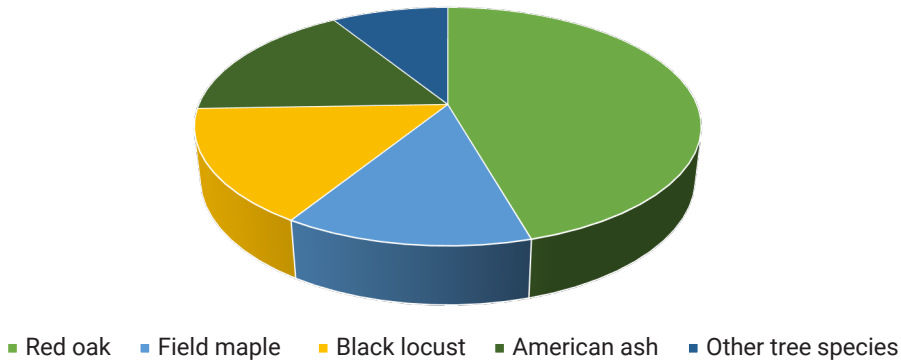


Figure 1. The structure of protective forest plantations within the agricultural landscapes of Ukraine

Source: compiled by the authors based on State Agency of Forest Resources of Ukraine (2020)

Overall, in Ukraine, the indicator of protective afforestation coverage averages 1.4%, while the optimal level is 4-5% (Kravchuk & Hutsol, 2019). Thus, it can be seen that the area of protective forest plantations needs to be increased by at least three times to optimize the agro-landscape protection system. However, currently, there is a reverse trend in Ukraine, causing significant concern among scientists. The priority functionality in the system of PFPs is determined by the structure of the plantation, which is a combination of parameters such as species composition, canopy structure, and width. Dense and open basic constructions are usually distinguished, with intermediate constructions between them. The analysis of the taxonomic characteristics of forest plantations within agro-forest-meliorative complexes, representative of the territory of Ukraine, convincingly positions species such as common oak, weeping birch, common ash, and poplar as priorities. They are recommended as the main species in PFPs, ensuring effective protection of agro-landscapes (Abu Dib, 2022). It is evident that an optimized PFPs system should guarantee the formation of a stable agro-forest landscape, stabilization of local and regional ecological

conditions, and the provision of optimal conditions for the functioning of agro-landscapes.

The moisture-regulating properties of protective forest plantations are determined by a combination of aspects such as the comprehensive interaction of all forest elements, the functionality of the forest litter, optimal soil structure, conditions for vertical water drainage, snowdrift prolongation, and protection against soil freezing. Anti-erosion forest plantations have specific functionality that mitigates erosion processes, regenerates the condition of erosion-affected soils, and ensures the balance of landscapes. It is important to note that the forest litter has significant water conservation and soil-protective value. It protects the soil from erosion, excessive compaction, and drying while acting as a filter. The litter allows excess moisture to pass through, promotes the transfer of surface run-off to groundwater, optimizes the physical structure of the soil, and contributes to the intensive biological cycling of substances in the forest plantation (Bida *et al.*, 2022). The water conservation properties of the forest litter are crucial for the sustainable functioning of agro-forest-meliorative complexes, leading to specific requirements for the

structure of protective plantations. It should ensure the formation of litter with improved qualities, including significant thickness and looseness, as well as a high calcium content. Shrubby species, as well as linden, ash, pine, oak, and birch, meet these requirements (Furdychko & Tymochko, 2020; Abu Dib, 2022). Moreover, they have maximum water-holding capacity.

As an optimum, the model of the optimal structure of PFPs should be positioned considering the functionality of their structure, with a focus on prioritizing species optimization directions. On arable slopes, it is appropriate to apply the functionality of protective and wind-regulating forest strips. It is evident that in the development of fringe and protective forest plantations, their most effective design solutions should be implemented, considering the natural features of regional ecosystems. For instance, open forest belts are advisable in regions with dust storms, and windbreaks are suitable for locations with cold and snowy winters. It is worth noting that FPFS (Forest Protective and Functional Systems), depending on the concept of agro-forest-melioration system, are formed in a pure or mixed form. Typically, they include one main species with slow growth rates. To enhance the protective functions of FPFS, a fast-growing species is introduced into the inter-forest row. On chestnut soils and southern chernozems, it is advisable to introduce up to 35% of low-growing shrubs in a rotational pattern with tree species (Schwarz *et al.*, 2021; Amons & Krasnyak, 2023). FPFS on irrigated lands are usually formed with an open structure in combination with windbreaks.

Anti-erosion plantations with the most optimal composition are positioned as mixed plantations with a combination of tree species and shrubs. Functional features determine their optimal structure. The implementation of effective PFPs systems is also influenced by natural-climatic features and landscape char-

acteristics. Additionally, the process is affected by the possibilities of agronomy in providing favourable development conditions. During the practical implementation of agro-meliorative measures, these requirements are often overlooked, leading to the destruction of meliorative characteristics and a decrease in the efficiency of PFPs (Savchuk & Liubchych, 2019; Pantera *et al.*, 2021). However, research indicates a significant ecologically stabilizing effect of agro-forest-meliorative plantations. The fundamental goal of optimizing the species structure of PFPs is to maximize the utilization of natural potential, considering the type of forest plant conditions. This potential can be effectively manifested only in conditions favourable for a particular species. In addition, determining factors for choosing the optimal structure of PFPs include their species diversity, the selection of effective main and accompanying species, their purpose, territorial location, and mixing.

The formation of PFPs in terms of their species categories currently cannot guarantee the prospective optimal balance between protective forests and plantations. The intensification of agro-forest landscapes for production purposes has significantly reorganized land resources, intensifying processes of deforestation and erosive destruction. Under these circumstances, the significance of PFPs with different purposes as a priority stabilizing factor in agro-forest ecosystems is highlighted. The experience of developed countries regarding the successful implementation of modern agro-meliorative systems underscores the need to revitalize protective forest plantations as a fundamental structural unit of contemporary agro-landscapes. For instance, the Sloping Agricultural Land Technology (SALT) method is successfully used to combat soil erosion and enhance crop yields (Zinngrebe *et al.*, 2020). In this approach, both protective tree-shrub plantations and vegetables/legumes are planted

in contour lines across slopes. This way, trees prevent erosion processes, and their leaves and organic matter enrich the soil.

In the United States, there is an effective combination of trees and shrubs with agricultural crops and livestock on the same land plot. This method improves soil fertility, prevents erosion, and promotes biodiversity (Schwarz *et al.*, 2021). There is an urgent need to establish comprehensive protective forest systems for agro-landscapes of various scales, including through the integration of individual PFPs and areas earmarked for future afforestation. The concept of enhancing the functionality of protective plantations of different purposes should be based on a landscape-ecological approach,

ensuring the formation of a stable agro-forest landscape. Such an approach will stabilize the environmental situation, regenerate regional resource potential, create optimal conditions for the development of agro-landscape complexes, and contribute to the balanced functioning of forestry in the agrosphere, enhancing the effectiveness of the biospheric functionality of forest ecosystems. An algorithm for the effective planting of trees to fulfil protective functions can be proposed, consisting of five qualitative stages of development for massive anti-erosion forest plantations (Table 1). The phased nature of the formation scheme ensures the effectiveness of the regeneration of the ecological balance in areas affected by erosion processes.

Table 1. Stages of ecological regeneration of agrolandscapes using protective forest plantations

Stage number	Period, years	Qualitative changes in the landscape
I	1-7	The gradual influence of artificially created protective forest plantations on ecological parameters, the reduction of the manifestation of erosion processes, the beginning closure of plantations.
II	8-14	Closure of the canopy, formation of a protective layer of forest litter, minimization of erosion, activation of biological soil processes, succession of living above-ground cover.
III	15-30	Intensive differentiation of trees, formation of tree stands and other components of the protective plantation (undergrowth, undergrowth, living topsoil), optimization of soil properties, establishment of a small cycle of substances, complete cessation of the development of erosion processes.
IV	31-55	Formation of sustainable forest ecosystems, regeneration of lost soil properties, intensification of soil formation processes, formation of the ability of protective forest plantations to natural recovery and anti-erosion impact on adjacent territories.
V	after 55	Restoring the ecological balance of eroded territories, increasing the area of their optimization impact on the landscape.

Source: compiled by the authors based on O.I. Furdychko & I.I. Tymochko (2020), A. Pantera *et al.* (2021), S.M. Abu Dib (2022)

Forest species in agro-forestry systems (main, accompanying, shrub) are identified based on the characteristics of forest conditions and soil-climatic features (Ladychenko *et al.*, 2022). Typically, the structure is formed by one main species, with a mandatory proportion of accompanying species. To enhance protective

efficiency and biological resilience, the introduction of shrub species, often fruit-bearing, is considered appropriate for Steppe and Southern Forest-Steppe forest plantations. The common oak is identified as the primary main species for forest belts in Polissia, Chernozem Steppe, and Forest-Steppe, being a tall and long-lived

species (Abu Dib, 2022; Savchuk & Liubchych, 2019). It is established that the extreme rows of protective plantations should include accompanying fruit-bearing species, such as common pear, cherry, white mulberry, wild apple, and walnut. In Polissia and Forest-Steppe, pendulous birch is introduced in the extreme rows, while in the middle rows, common pine is considered appropriate. However, the formation of pure pine plantations is considered inefficient.

In Steppe conditions, honey locust is suitable as a fast-growing species on chernozem soils, while for the Southern Steppe, small-leaved elm and white acacia are the priority species. Poplar plantations are formed in both pure and mixed forms, alternating with accompanying fruit-bearing species in Forest-Steppe and Polissia, while in Steppe, a combination with shrub species is preferred (Kravchuk & Hutsol, 2019; Amons & Krasnyak, 2023). The optimization of the structure of forest plantations with agro-meliorative functional orientation requires the mandatory consideration of soil conditions. It is advisable to prefer species that, based on years of experience, demonstrate maximum local resistance and longevity (such as sharp-fruited ash, Japanese sophora, feathered elm) (Kravchuk & Hutsol, 2019; Koval, 2023). On stony soils, coniferous species should be included in the structural-species composition of plantations. On irrigated lands, it is appropriate to form forest plantations, involving species like walnut and various types of poplar. On saline soils, tree species such as Crimean pine, narrow-leaved olive, Tatar honeysuckle, and Canadian redbud should be introduced (Mishenin *et al.*, 2021b).

The process of forming an optimal structure for forest ecosystems within agro-meliorative complexes involves maximizing the share of protective forest plantations in all natural zones of Ukraine, optimizing the species composition of PFPs, implementing

agro-meliorative measures and protective afforestation, applying monitoring of PFPs based on geoinformation technologies. Such a conceptual approach allows the regeneration of the environmental potential and increases the resilience of forest-meliorative ecosystems, optimize the placement of protective forest plantations, increase the yield of agricultural crops, and ensure the additional absorption of greenhouse gases.

Discussion

The features of the relationship between the agroforestry meliorative system and the structure of forest ecosystems have long been a subject of broad scientific interest among modern researchers. Many scientists focus on the general aspects of the impact of agro-melioration on forest plantations within agroecosystems, as well as on the ecological and economic consequences of irrational forest meliorative measures or their absence. Each of them has made a significant contribution to understanding the relationships between soil and phytocoenosis or laid the foundations for sustainable agrolandscape use through agroforestry methods. For instance, S. Fahad *et al.* (2022) argue that protective forest plantations are the basis for soil protection against erosion processes, positioning themselves as the foundation of forest melioration. S. Jiang *et al.* (2022) and F.M. Santos *et al.* (2021) emphasize the undeniable impact of PFPs on increasing crop productivity, optimizing temperature and water regimes, and preventing soil degradation. Scientists see an additional positive effect in reducing wind speed, protecting against excessive drying and blowing away of the top fertile soil layer.

Analysis of current scientific research summarizes that areas with existing PFP systems in agricultural landscapes create significantly more favourable ecological conditions for the sustainable functioning of agrolandscapes.

Modern researchers, led by S. Chen *et al.* (2022), highlight the crucial importance of the optimal species structure of PFPs for the performance indicators of the agroforestry melioration system. These research results align with conclusions in the context of updating the algorithm for effective structuring of forest ecosystems within agroforest landscape complexes. The main idea of these findings is further developed in the works of F. Montagnini & S. del Fierro (2022) and Y. Zinngrebe *et al.* (2020), who suggest that for the optimization of FPFS in Ukraine, a profound reconstruction and regeneration of protective forest plantations are necessary. According to researchers, this work should be carried out based on scientifically grounded recommendations within special state programs, including those outlined in the “Concept of Agroforestry Development in Ukraine” (2013). Scientists forecast that priority directions in scientific and practical work in this area should include restoring the protective functions of forest strips, ecological balance, and stimulating the productivity of agrolandscapes.

Z. Marais *et al.* (2022) in their research draw special attention to the need for improving the management system for agroforestry melioration development, their accounting, and control, which would, to some extent, stabilize existing negative natural processes in agrolandscapes. This fact is developed in the scientific works of D. Octavia *et al.* (2022), emphasizing the multiple increase in the risks of destructive consequences of prolonged anthropogenic influences and highlighting the need for effective protection of agrolandscapes. A comprehensive approach to the functioning of agroforestry meliorative complexes involves indicating aspects of the local ecological situation. The basis of intensive ecological impact by PFPs should consist of main long-lived tree species at the land use boundaries and in

large crop rotations. Simultaneously, the precondition for the effectiveness of optimization measures is the updating of the regulatory framework and legal field in the field of agroforestry melioration (Prakhovnik *et al.*, 2022). This issue is developed in the works of modern scientists M. Santos *et al.* (2022) and S. Sorge *et al.* (2022). Researchers emphasize that with effective management regulation of the increase in PFP areas and the fundamental conceptual provisions of agroforestry melioration, significant ecological and economic effects can be achieved. The conclusions of scientists need to be supplemented in terms of differentiating the above-mentioned effect, as, according to the current research, it can manifest directly, such as increasing crop yield or protecting land from erosion, as well as indirectly, in terms of preserving biological diversity and optimizing the local and regional ecological situation.

Comparing the results of this study with M.T. Sri Budiastuti *et al.* (2021), the common conclusion is that the primary causes of the destruction of protective plantations are identified as their unsatisfactory sanitary condition, uncontrolled growth processes, and irrational structural and species composition. However, the main precondition for the degradation of the agroforestry melioration system is the legal vulnerability of FPFS (Puzrina *et al.*, 2022). This thesis is consistent with the works of scientists J. Xiao & K. Xiong (2022), who argue that, mostly, official information regarding the real qualitative and quantitative state of FPFS does not correspond to reality today. The absence of sanitary and care logging is a separate problem that has intensified during wartime. This is emphasized by several researchers, including G.C. de Mendonça *et al.* (2022). Correlating the statements of scientists with the results of this study, it can be highlighted that due to the disruption of the structure, protective forest plantations become overgrown, weed-infested, and filled

with unwanted shrubby vegetation, losing their water-regulating and ventilating properties.

The pressing issue is the need to create unified synergized systems of protective forest plantations for various natural-ecological conditions, studied during the research, and also discussed in the works of D.A. Martin *et al.* (2020) and V. Rolo *et al.* (2023). Scientists advocate for fundamental changes in the legal regulation of stabilizing components of agroecosystems by achieving their optimal ratio, sustainable functioning, and increased productivity. Despite the identical results of this study to the conclusions of other researchers, it is essential to emphasize the significance of the relationships between the state of individual forest ecosystems and the agrolandscape complex as a whole. The concept of optimizing the structure of forest ecosystems affected by agroforestry melioration measures should be based on landscape management principles involving agroforestry methods, following the principles of balanced sustainable development (Abaikyzy *et al.*, 2020). Similarly, scientists A. Nuddin *et al.* (2019) draw attention to the need for timely monitoring of the agroforestry melioration system. It is challenging to disagree with the researchers' conclusions, considering the risks of indirect impacts that often go unnoticed but are equally significant due to their continuous, multifaceted, and large-scale nature. The main direction of optimization in the studied area, according to scientists, should be the creation of a unified database of forest-taxon characteristics of agroforestry plantations. For effective inventory and monitoring of agroforestry plantations, the application of unmanned aerial vehicles, geoinformation technologies, and online cartographic services is considered prospective (Fedoniuk & Skydan, 2023).

O.P. Tkachuk & N.G. Viter (2022) in their scientific research correlate with the findings of this study regarding the need to form PFPs in

an optimal volume, creating opportunities for optimizing Ukraine's national ecological network, regenerating natural ecosystems and agrolandscapes, ensuring favourable conditions for increased productivity and agricultural ecologicalization, as well as actively influencing regional climatic characteristics. Despite the numerous publications dedicated to agroforestry melioration, there is a need for detailed research on its impact on the structure of forest ecosystems within a unified landscape complex. Despite the active position of leading scientists in the field of agroforestry melioration, the overall state of the industry in Ukraine is undergoing gradual destruction, and protective forest strips suffer from uncontrolled logging (Reshetilov, 2022). Therefore, the topicalization of the issues of protective forest cultivation and the popularization of the studied topics in the scientific community are deemed necessary.

The aim of future scientific research in this direction should be to identify strategic priorities for the formation and integration of practical measures to optimize the structure of agroforestry protective plantations. In the functional aspect of further research, it is considered appropriate to apply landscape-ecological principles as the basis for the concept of forming a sustainable agroforestry landscape. This concept should ensure the maximum efficiency of rational placement and optimal ratio of PFPs in agrolandscape complexes, compliance with their regulatory parameters, and a rational structural-species configuration.

Conclusions

The process of implementing the principles of sustainable land use and the development of agroecosystems involves optimizing the structure of protective plantations through the application of innovative approaches to agroforestry melioration algorithms. During the conducted research, the vector nature of

interdependencies between the agroforestry melioration system and the structure of related forest ecosystems was clarified. The peculiarities of the destruction of the agroforestry melioration system in Ukraine were identified. It was established that the optimization system of measures based on scientific grounds for the formation of sustainable agroforestry meliorative complexes in Ukraine is currently not functioning properly. The study identified the urgent need for the development of optimization measures for the formation of a stable genetic forest component of agroecosystems based on landscape-ecological differentiation.

The research successfully identified the features of the species structure of protective forest plantations in Ukraine, pinpointing the basic priority tree species for the formation of functional PFPs. The primacy of conceptual landscape-ecological principles and the principles of developing a sustainable agroforestry landscape during the optimization of the structure of protective forest plantations of various purposes were substantiated. The adaptation of regulatory and legal support and control in the researched area, as well as the implementation of an innovative modern system of environmental monitoring for the agroforestry meliorative complex, including the utilization of advanced

geoinformation system capabilities, were justified. During the research, significant efforts were synergized to demonstrate the need for vectoring the impact of agroforestry melioration on the structure of forest ecosystems in terms of stabilizing the environmental state, preserving the natural resource potential, and providing optimal conditions for increasing the productivity of agrolandscapes. Recommendations regarding the assortment of tree species for protective forest plantations under different forest-plant conditions were developed.

Based on the conclusions obtained from the research, priority directions for further scientific research on the investigated topic were developed, justifying the need to update the issues of the agroforestry melioration system in Ukraine at the national level. The necessity for a deep and detailed development of practical measures for the regeneration of forest ecosystems within agroforestry meliorative complexes, in the aspect of optimizing the structure of plantations, was highlighted.

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Conflict of Interest

None.

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Вплив агролісомеліорації на формування структури лісових екосистем

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Анотація. Функціональне навантаження лісів зумовлює актуалізацію меліоративних заходів для оптимізації функціонування агроландшафтних комплексів. Ці заходи сприяють покращенню екологічної ситуації та розвитку в напрямку стійкого функціонування лісових екосистем. Саме тому дослідження структурно-видового формування лісових екосистем викликає суттєвий науковий інтерес. Мета статті полягала у проведенні аналізу впливу агролісомеліоративних заходів на процес формування структури лісових екосистем у сукупності взаємозв'язків. Дослідження проводилось із залученням загальних методів наукового пізнання, у тому числі, конкретизації, дедукції, системного аналізу, синтезу та абстрагування, формалізації. Під час проведення дослідження проаналізовано вектори організації оптимізованих систем захисних лісових насаджень, обґрунтовано природоохоронні пріоритети розвитку агролісових екосистем. Виокремлено базові принципи управління комплексом агролісомеліорації на засадах сталого природокористування, серед яких – комплексний підхід, екологізація процесу та постійний моніторинг. В дослідженні виявлено актуальні екологічні наслідки нераціональної меліорації для лісових насаджень, зокрема, посилення ерозійних процесів та деградацію земельних ресурсів, виокремлено ризики та виклики, котрі вимагають превентивних рішень. Доведено, що збільшення частки

агролісомеліоративних насаджень дасть змогу оптимізувати екологічну ситуацію в Україні, сприятиме регенерації природної ресурсної бази та відновленню ландшафтів, мінімізує процеси деградації земельних ресурсів. Запропоновано основні заходи з оптимізації екологічної ситуації на локальному рівні лісових екосистем, а також превентивні міри для запобігання деструктивному впливу, зокрема, вдосконалення правового забезпечення та впровадження жорстких мір відповідальності за нераціональне ресурсокористування. Цінність висновків вбачається в доцільності їх практичного використання для моніторингових досліджень стану та процесу формування структури лісових екосистем під впливом реалізації агролісомеліоративних заходів, а також задля ефективної розробки превентивних і регенераційних захисних мір та формування збалансованих лісових екосистем

Ключові слова: захисні насадження; ерозійні процеси; моніторинг; районування; потенційні ризики; асортимент деревних рослин

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Ecological and biological features of the selected forms of checker tree for successful targeted introduction and reintroduction into the ecological network of Ukraine

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Abstract. The study considers the issues of introduction and reintroduction of the Red Book species of checker tree in the system of decorative gardening, forest protection, and forest ecosystems. That is why the purpose of the study was to monitor the green corridors of rural and urban ecosystems of the forest-steppe zone of Ukraine, to investigate and select the best forms of checker tree in terms of morphological characteristics and physiological properties for promising areas of distribution and conservation in the form of pure and mixed plantings. The following methods were used in the research: route, field, biometric, laboratory, comparative analysis, mathematical and statistical. New forms of checker tree were introduced, studied in *in situ* and *ex situ* conditions, and selected for the prospects of their further introduction and reintroduction into the ecological network of Ukraine and conservation to activate trophic, phoric, and other types of biotic interactions in a single territorial ecosystem. Sparsely distributed biotypes of *Torminalis glaberrima* (Gand.) Sennikov & Kurtto f. *Intermedia* Kossetz were found in the zone of green corridors of rural and urban ecosystems of the forest-steppe zone of Ukraine. Some specimens of these biotypes were identified as valuable material for introduction into the system of fruit and ornamental gardening, including parks and monuments of landscape art, as well as natural monuments, protected tracts, sanctuaries and reserves of pure and mixed plantings, alleys, forest reclamation strips, etc. It was established that the elements of originality of the selected forms of checker tree – Eva, Podolianochka and Slavka – are the specificity of the crown shape, which determines the level of productivity, small and medium growth force, normal reaction to pruning (which affects the size and yield of fruits), high degree of flowering (60-80%), increased fruit size (diameter of more than 2 cm), increased fruit weight (1.8-2.1 g), increased number of fruits on the stem (≥ 20 units), a pleasant and harmonious taste of fruits, high quality of fruits, lack of periodicity in fruiting in nature and in culture, high xenogamy (69-75%), high yield of fruits from the plant, increased winter hardiness (7.5 pt.), high drought resistance (8 pt.) and resistance to pests, including pear leaf blister mite (7-9 pt.). The findings can be used in the future to replenish pure and mixed plantings in the ecological network of Ukraine

Keywords: *Torminalis glaberrima* (Gand.) Sennikov & Kurttof. *Intermedia* Kossetz.; biochemical properties; new biotypes; replenishment of the ecological network; Red Book species; ascorbic acid content

Introduction

Forest ecosystems, as an object of the ecological network, are considered necessary as reservoirs of biological diversity, oxygen producers, and carbon dioxide sinks. Modern threats to forest ecosystems, such as the loss of biodiversity, often disrupt their biological integrity and ecological functions. M. Breil *et al.* (2023) note that broad-leaved forests are characterised by a higher albedo, are marked by reduced stomatal resistance and greater branching of the root system, compared to coniferous forests,

in addition, deciduous forests, which include checker trees, absorb less solar radiation spectra, and therefore, the process of evaporation of accumulated water is less intense. But historically, deciduous forests were used for cutting and clearing land for agricultural purposes, and then gave way to urbanisation. As reported by H. Lundmark (2020), in Europe, forests have been used since prehistoric times for various purposes, such as forest pastures, silvicultural reclamation, and logging.

Currently, only 1% of the original forest remains in Central Europe (Sabatini *et al.*, 2021). In this regard, the introduction of endangered species stocks, which have almost no viable places for reintroduction to foreign locations, is gaining relevance. Therefore, significant progress has also been made for some ecologically threatened and endangered species, with new biotechnological advances that have made reintroduction affordable (Douglass *et al.*, 2023). However, as noted by M. Gastauer *et al.* (2021), environmental laws in many countries require the use of native species to restore destroyed land through the reintroduction of native species. As noted by C.E. Aslan (2019), alien plant species intentionally imported or distributed naturally from neighbouring areas can harm public health, biodiversity, and the overall ecosystem.

Y.A. Othman *et al.* (2023) note that the conservation of endangered plant species in their native regions is crucial. According to J.M. Werres (2018), checker tree is one of the tree species that is on the verge of extinction, which inevitably affects the normal course of biological processes, for example, plants of this species are the food base for many birds and mammals, etc. In this regard, it is necessary to monitor the biodiversity of forest ecosystems, preserve checker trees and select the most productive and ecologically adaptive specimens, whose high vitality will determine their growth and development in the forest ecosystem. It should be borne in mind that if checker trees have been eradicated from certain forest ecosystems where they previously existed, new specimens that will make up the re-introduced population should be taken from wild populations. When selecting tree specimens for reintroduction, it is important to consider local adaptation, adaptation to *ex situ* conditions, the possibility of inbreeding and outbreeding depression, and the taxonomy, ecology, and genetic diversity of the original population. Therefore, care should be

taken to avoid inbreeding and inbreeding depression. During reintroduction of species, it is proposed to cover as much genetic diversity as possible, which is measured as heterozygosity.

Plants undergoing reintroduction may show reduced fitness if they are not sufficiently adapted to local environmental conditions. In this regard, researchers should consider the ecological similarity of source and recipient sites when choosing populations for reintroduction. As noted by M. Löf *et al.* (2019), to ensure the functioning of the ecosystem in the future, checker tree recovery programmes must integrate ecological knowledge, best practices and regeneration systems, overcome biotic and abiotic disturbances, and adapt to future forest landscapes. In this regard, historically, the source of plant material for reintroduction has followed the “local is best” rule as the best way to preserve local adaptations, with specimens for reintroduction selected from the closest geographical population. For plants, minimisation of adaptation to captivity is usually achieved by obtaining plant material from a seed bank, where specimens are stored as seeds collected in the wild and have not had the opportunity to adapt to captive conditions. However, this method is only possible for plants with dormant seeds.

According to M.M. Rahman *et al.* (2018), *ex situ* conservation of endangered species of checker tree is important for sustainable use of forest genetic resources in Ukraine. N.P. Schpak *et al.* (2020) substantiated the feasibility of introducing checker tree into hornbeam, beech or oak cultures as a fitting species and as a forest soil structurer. However, the issues of targeted introduction and reintroduction to the ecological network system of Ukraine remain open. As stated By I. Robiansyah & Dodo (2022), for the successful process of reintroduction of checker tree, among other things, it is important to involve local

communities in the care or supervision of plants, and to prevent and reduce disturbances in the area of conservation activities and for the effective management of certain activities.

Reintroduction of checker tree in light broad-leaved forests and oak stands, where they fell under the influence of anthropogenic factors, contributes to the restoration and preservation of plants. This strategy may involve planting them in pristine forest ecosystems or restoring degraded ecosystems that promote long-term plant viability. An important part of this approach is to integrate management with the environment to ensure their long-term conservation.

The purpose of the study was to monitor the green zone of rural and urban ecosystems of the forest-steppe zone of Ukraine to select the best forms of checker tree in terms of morphological characteristics and physiological properties for promising areas of their introduction and reintroduction into the ecological network of Ukraine.

Materials and Methods

Stationary research was conducted on the territory of the Institute of Horticulture of the National Academy of Agrarian Sciences (NAAS) of Ukraine and its scientific network (Lviv Oblast) during 2017-2021, expeditionary research – 2015-2021 in forest parks of rural and urban ecosystems in Kamianets-Podilskyi district of Khmelnytskyi Oblast (Ukraine). The search for checker tree localities was carried out in the Kamianets-Podilskyi district (green zone of the urban ecosystem of Kamianets-Podilskyi, the outskirts of the Suprunkivtsi village).

To select the best forms of checker trees, the methodology of forestry and taxation studies by N. Anuchin and R. Anoshin was used to determine the biometric parameters of the stand. Phenological observations were performed according to N.I. Bazilevich. The flowering phase and fruiting abundance were

evaluated according to V.G. Kapper. Considerable attention was paid to the study of morphological features of the inflorescence, flower, and focused on the definition of the degree of flowering. Biometric assessments of plants included determining: height, growth strength, direction of placement of skeletal branches, position relative to the trunk and angle of their placement, crown and trunk diameter, crown density and shape, tree habitus.

At the Institute of Horticulture of the National Academy of Agrarian Sciences of Ukraine and its scientific network, grafted plantations of selected checker tree forms were established (*ex situ*) and studied for biometric parameters, winter hardiness (Sokolov, 1957), and drought resistance (Pyatnitsky, 1976).

To investigate specimens of checker tree by morpho-physiological characteristics and properties, several breeding forms were selected: Eva, Podolianochka, and Slavka, the intraspecific taxon of which was *Torminalis glaberrima* (Gand.) Sennikov & Kurtto, belonging to the variety *T. glaberrima* (Gand.) Sennikov & Kurtto. f. *intermedia* Kosetz. In addition, morphological features of vegetative and generative buds, shoots, leaves (density of placement at the end of the shoot, size, intensity of green colour, cross-section profile, intensity of anthocyanin colour, glossiness, pubescence on the upper and lower sides, type and format of the apex, shape of the base and edge, type of venation, number of blades, time of onset of yellow, red leaf colour time of leaf fall), inflorescences (type, diameter, number of flowers), flowers (diameter, calyx in height, position of the stigma relative to the anthers, pedicel by length, shape of anthers, number of anthers, colour of the base of the staminate thread, colour of the underside of the petals, position of the petals, location of the petals, number of petals, colour of the anther), fruit (height, width, diameter, uniformity of ripeness, main colour of the peel,

glossiness of the peel, density of the lenticel location, weight, surface texture, aroma, shape, peduncle in length, pubescence of the peel, villi in density, colour of the villi, depth of the calyx, colour of the pulp, weight of 1,000 fruits, number of fruits on the corymb, the number of seeds in the fruit). The abundance of fruiting

was evaluated on a 6-point scale of visual yield assessment according to V.G. Kapper. Phenological observations were performed according to I. Beideman.

Drought resistance during the growing season was determined on the scale by S.S. Pyatnitsky (1976) (Table 1).

Table 1. Scale of evaluation of checker tree plants for drought resistance

Signs of drought resistance	Score
No signs of drought damage	5
Leaves lose water in the daytime, are in a state of plasmolysis, restore turgor in the dark	4
Leaves of the lower tier lose colour, dry up and fall off, but the shoots of the upper tier are characterised by normal growth and development	3
Almost all leaves dry out without changing colour, but the shoots do not lose their viability and next season resume development due to apical buds.	2
Almost all leaves and tops of annual shoots dry out without changing colour	1
Plant dies	0

Source: S.S. Pyatnitsky (1976)

The intensity of damage by pests and diseases was determined visually guided by the educational and methodological work of I.M. Mrynskyi & T.M. Tymoshchuk (2022). The analysis of the age structure of checker tree habitat areas was carried out following the generally accepted methodology and according to the recommendations of I.V. Semechkin and E.N. Ioshchenko & N.N. Lashchinsky. The degree of flowering was estimated according to O.A. Kalinichenko (2003), abundance of fruiting – according to V.G. Kapper.

Determination of taste and tasting assessment was carried out according to S.O Tkachyk (2016), Methodology for examination of fruit, berry, nut, and grape plant varieties for distinction, homogeneity, and stability (2022).

Biochemical analyses of checker tree fruits were carried out in the laboratory of selection and technology of growing berry crops and the laboratory of post-harvest quality of fruit and berry products of the Institute of Horticulture of the National Academy of Sciences and independent laboratories for assessing the quality of fruits.

The content of pectin substances was monitored according to DSTU 8069:2015 (2017), ascorbic acid – DSTU ISO 6557-2:2014 (2015). The study considered the standards of the Convention on the Trade in Endangered Species of Wild Fauna and Flora (1979) and Convention on Biological Diversity (1992). The study data were statistically processed in the Excel-2007 software suite.

Results and Discussion

In September 2022, new forms of checker tree were included in the Genetic Bank of Ukraine based on a successful examination conducted by the National Centre for Plant Genetic Resources of Ukraine (Kharkiv). The introduced specimens were studied for morphological traits, biological properties, and economic characteristics and are stored in the collection of the Institute of Horticulture of the National Academy of Agrarian Sciences of Ukraine (Novosilky village, Fastiv district, Kyiv Oblast) and the Podilskia Rozkish fruit and berry mini-nursery (Muksha Kitaygorodska village, Kamianets-Podilskyi district, Khmelnytskyi Oblast).

The *Eva* specimen of checker tree (certificate No. 2375, National catalogue No. UN0700091) belongs to the category of wild form, discovered and selected in 2015 at the border of Suprunkivtsi village (Kamianets-Podilskyi district, Khmelnytskyi Oblast). The wild form of *Eva* is registered as a sample of the gene pool based on the following originality elements: a combination of fruit weight of 2.1 g, fruit diameter of 2.2 cm, ascorbic acid content (55 mg/100 g of raw weight), tasting score of fruits of 8 points, high winter hardiness (7 pt.), drought resistance (8 pt.), with a fruit yield of 12.5 kg/plant.

In addition, the plants of are characterised by high plasticity relative to pruning, early time of maximum fruiting in culture (at the 3rd year), a high degree of flowering – 60-80%, increased self-fertilisation – 69%.

Signs of identification of a sample of checker tree *Eva*, which determine its difference (morphological, biochemical, etc.) life form – a conical tree with a rounded crown, a high number of skeletal branches (>10) and strong branching. The angle of position of skeletal branches relative to the trunk is 45° at a height of 1.5 m (Fig. 1).



Figure 1. Plant (tree) of the wild form of *Eva* checker tree

Source: photo by the authors

Plants of the *Eva* specimen are characterised by high growth power (0.36 m/vegetation). The size of the vegetative buds is small (6 mm), the colour of the vegetative bud is dark cherry, the position of the vegetative bud relative to the shoot is slightly deviated. The time of the beginning of the development of vegetative buds is average (the end of the 3rd ten days of March – the beginning of the 1st ten days of April) and the time of flowering of vegetative buds (the appearance of leaves) is also average (the 2nd ten days of April). Annual shoot: medi-

um thickness (4.5 mm). The colour of the bark of the annual shoot is olive-grey with numerous lenticels, which give it a specific grey hue. The size of the bud base on an annual shoot is average (6 mm). The intensity of the green colour of the leaf is moderate, the size of the leaf is average (13.2×11.9 cm), the shape is pointed-ovate lobed and dissected, the leaf type is simple, and the type of its tip is pointed and drawn, the shape of the base is slightly truncated or notched, the shape of the edge is biserrate, the length of the petiole is medium (4 cm), the

pubescence on the upper side of the leaf is absent, the lower side is absent or weak, the number of blades on the leaf is 7. The density of leaf placement at the top of the shoot is average

(4 units). It was found that the time of the onset of yellow leaf colour is average (the end of the 2nd – beginning of the 3rd ten days of September) and the time of leaf fall is also average (Fig. 2).

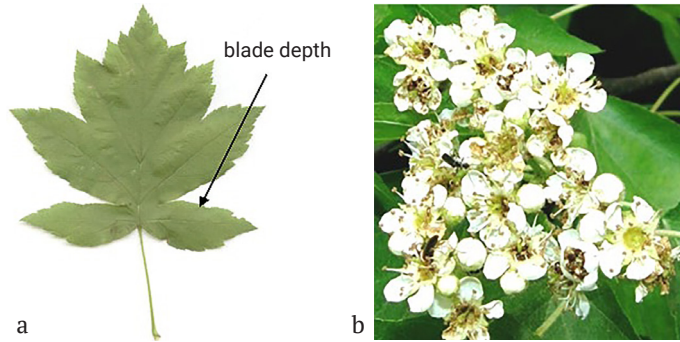


Figure 2. Leaf (a) and inflorescence (b) of checker tree form Eva

Source: photo by the authors

The inflorescence of Eva checker tree is a medium-sized corymb (average diameter – 18 cm), the flower is medium in diameter ($d=1.6$ cm), five – petalled, the perianth petals are white, intersecting, placed horizontally (Fig. 2). Placement of the flower stigma relative to the anthers is lower. The number of stamens is 20. The colour of the anthers is dark yellow or yellow and orange. Pedicel pubescence is weak. The number of flowers on the corymb is average (48). The fruit of the plants is an apple, with a large diameter ($d=2.2$ cm). It should be noted that the time of the beginning of flowering is average (the beginning of the 2nd ten days of May). The degree (signs) of flowering is a maximum of 4 points, or 60-80%, which is very good in rank. The self-fertilisation rate of Eva plants is high (69%). The ripeness group of the Eva sample is average. The time of the beginning of maturation depends on weather conditions and may fall at the end of the 3rd ten days of August, and the 1st ten days of September or the 2nd ten days of October. A similar dependence is observed with regard to the onset of the phases

of vegetative buds, budding and flowering, etc. Morphological characteristics of the fruit are as follows: the fruit is tall (2.3 cm), medium in width (2.5 cm), medium weight (2.1 g), colour – light brown, pulp colour – brown, shape – elliptical or broadly oval, peduncle is long (5.5 cm), depth of the calyx – closed, lenticels are located on the skin tightly, the texture of the skin surface is smooth or slightly rustling, the skin pubescence is weak, the colour of the pubescence (villi) is white (Fig. 3).



Figure 3. Checker tree fruits of the Eva form
Source: photo by the authors

The taste of the fruit is moderately sweet with a slight sourness, fruity with hints of dried apricots. The tasting rating of fruits is high (8 points). The number of seeds in the fruit is small (0-3 units). The seed colour is light chestnut or brown. Uniformity of fruit ripening: uniform (in culture) and not uniform (in nature). The number of fruits on the corymb is average (19). The abundance of fruiting of plants is average or good – 3.5 points. It is established that the time (age) of the onset of maximum fruiting from the seedling is late (8 or more years), but the time (age) of the onset of maximum fruiting on the scion is early and is 2-3 years. It was found that checker tree plants are very plastic and in culture, subject to the observance of care systems, are able to form a high fruit yield at the age of 10-15 years, exceeding 10 kg/plant. For wild-type Eva plants, the average fruit yield at the age of 29 is about 12.5 kg/plant. The fruiting cycle is periodic.

The Podolianochka specimen of checker tree (certificate No. 2377, National catalogue No. UN0700092) belongs to the category of wild form, discovered and selected in 2015 in the park area of Kamianets-Podilskyi, Khmelnytskyi Oblast. The wild form of Podolianochka was registered as a sample of the gene pool based on the following elements of originality: a combination of fruit weight of 1.9 g, a high number of fruits per stem – more than 20 units, drought resistance of 8 points, resistance to pear leaf blister mite of 9 points, with a fruit harvest of more than 10 kg from a plant at the age of 10 years. Pleasant harmonious taste of fruits. Cup-shaped crown, low growth force (0.25 m/vegetation), good reaction to pruning, no periodicity in fruiting in nature and culture, self-fertility – 75%.

Signs of identification of the wild form Podolianochka, which determine its difference: life form – a tree that ranges in habitus from straight to sprawling, the crown shape is transversely elliptical, a high number of

skeletal branches (>10), strong branching, the angle of position of skeletal branches relative to the trunk is 55° at a height of 1.5 m (Fig. 4).



Figure 4. Plant (tree) of the wild form of Podolianochka checker tree

Source: photo by the authors

Plants of Podolianochka form are characterised by a small size of vegetative bud (6 mm), the colour of vegetative bud is dark cherry, the shape of vegetative bud is blunt ovate, the position of vegetative bud relative to the shoot is slightly deviated, the intensity of green leaf colour is moderate, the leaf size is average, the leaf type is simple, the leaf shape is pointed-ovate dissected, leaf petiole length is average (4 cm), the inflorescence is a medium-sized corymb, with a diameter of 17 cm, flower in diameter – medium, perianth petals – white, intersecting, horizontally arranged, number of flowers in inflorescence – medium (45 units). Morphological features of fruits: medium diameter ($d=1.7$ cm), medium weight (1.8 g), shape – elliptical, or broadly oval, peduncle is long (5 cm), calyx is shallow (≥ 1 mm), colour – light brown, pulp colour – brown, seed colour – light chestnut or brown (Fig. 5).



Figure 5. Leaves and fruits of the wild form of Podolianochka checker tree

Source: photo by the authors

The taste of the fruit is moderately sweet with a slight sourness, fruity with hints of dried apricots, excellent aftertaste of dried fruits. It is also worth noting that the number of fruits on the corymb is average (11). The time of the beginning of ripening of fruits in the wild state is average (1st ten days of September), in culture on a scion – early (on 2nd–3rd years). The abundance of fruiting is average and is 3.5 points (average or good harvest). The average fruit yield at the age of 30 years is 10.6 kg/plant. The ripeness group is average.

The Slavka specimen of checker tree (certificate No. 2376, National catalogue No. UN0700090) belongs to the category of wild form, discovered and selected in 2015 in the park area of Kamianets-Podilskyi, Khmel-nitskyi Oblast. The wild form of Slavka is registered as a sample of the gene pool based on the following elements of originality: the specificity of the crown shape (cup-shaped), which determines the level of productivity, low growth force (0.25 m/vegetation, good reaction to pruning (which affects the size and yield of fruits), increased fruit weight (1.9 g), high number of fruits on the stem (≥ 20), pleasant harmonious taste of fruits, lack of periodicity in fruiting in nature and in culture, high self-fertility (75%), increased yield of fruits from the plant

(>15 kg/plant), by year (5 t/ha), increased winter hardiness (2 pt.), high drought resistance (4.5 pt.), high resistance to pear leaf blister mite (9 pt.).

Signs of identification of the Slavka specimen that determine its difference (morphological, biochemical, etc.): life form – a sprawling tree, crown shape – cup-shaped, a high number of skeletal branches (>10), strong branching, the angle of skeletal branches relative to the trunk is 55° at a height of 1.4 m (Fig. 6).



Figure 6. Plant (tree) of the wild form of Slavka checker tree

Source: photo by the authors

Plants of the above form are also characterised by a large size of the vegetative bud (>8 mm), the position of the vegetative bud relative to the shoot is compressed. The time of the beginning of the development of vegetative buds is average (the end of the 3rd ten days of March – the beginning of the 1st ten days of April), the time of flowering of vegetative buds (the appearance of leaves) is average (2nd ten days of April) and the time of flowering is also average (the beginning of the 2nd ten days of May). Morphological characteristics of the leaf are as follows: the intensity of the green colour

of the leaf is moderate, the size of the leaf is average (11.5×9.9 cm), the leaf type is simple, the shape of the leaf is pointed-ovate lobed, the length of the leaf petiole is medium (4 cm), there is no pubescence on the upper and lower sides, the type of the tip is pointed – stretched, the shape of the base is notched, the shape of the edge is biserrate, the number of blades is 7, the length of the petiole is average (4 cm), the density of placement at the end of the shoot is average (6 units). The time of the beginning of yellow leaf colour is average (late 2nd – early 3rd ten days of September). The time of leaf fall is also average and falls on (3rd ten days of October). Checker trees are characterised by an inflorescence in the form of a corymb of medi-

um size, with a diameter of 20 cm, the flower is average in diameter (d=1.5 cm), the perianth petals are white, intersect, placed horizontally. The number of flowers on the corymb is greater than for Eva and Podolianochka forms, and averages 58. Self-fertilisation for this specimen is high (more than 75%). Next, the study considers the morphological parameters of fruits: diameter – large (2.4 cm), density of the location of lenticels – average, shape – elliptical, or broadly oval, peduncle length – long (5 cm), skin hairiness – present, villi – whitish, colour – light brown, colour of the fruit pulp – brown, seed colour – light chestnut or brown. The fruit is tall (1.8 cm), average in width (1.5-2.2 cm), and the height-to-width ratio is average (Fig. 7).



Figure 7. Leaves and fruits of the wild form of Slavka checker tree

Source: photo by the authors

The tasting score of the fruit is above average or 7 points. The taste of the fruit is moderately sweet with a slight sourness, fruity with hints of dried apricots and raisins. The time of the beginning of fruit ripening is average (1st ten days of September). The average fruit yield at the age of 29 years is more than 15 kg/plant.

Notably, for new forms of checker trees, in addition to morphology, a biochemical analysis of fruits was carried out. It was found that for the forms of Slavka and Podolianochka, fruits in technical ripeness are characterised by an increased content of total sugars and polyphenolic compounds, compared to the Eva form (Table 2).

Table 2. Biochemical properties of fruits of new forms of checker tree

Qualitative parameters of the fruit	Form		
	Eva	Slavka	Podolianochka
Vitamin C, mg/100 g	55.0	38.0	48.0
Sugars (total amount), % of raw weight	8.6	12.43	10.4
Dry matter, % of raw weight	44.3	42.12	42.1
Dry soluble substance, % of raw weight	36.5	12.5	22.5
Titrated organic acids, % of raw weight	1.9	1.8	1.9
Pectin substances, % of raw weight	2.72	0.72	2.54
Polyphenolic compounds, mg/100 g	425.6	711.0	441.0
Flavonoids, mg/100 g of raw weight	6.7	6.9	6.0
Anthocyanins, mg/100 g of raw weight	0.6	0.7	0.7
Chalcones, mg/100 g of raw weight	2.44	2.6	2.17
Tasting score, points (1-9)**	high (8.0)	7.0	8.0
Sugar-acid index (SAI)	5.7	5.8	5.6
Fruit taste	moderately sweet with a slight sourness, fruity with hints of dried apricots	moderately sweet with a slight sourness, fruity with hints of dried apricots and raisins	moderately sweet with a slight sourness, fruity with hints of dried apricots, excellent aftertaste of dried fruits
Transportability, score (1-9)	9	8	8

Source: developed by the authors

Despite certain differences in the indicators of biochemical properties, the fruits of all the studied forms of checker tree have the same SAI and a high tasting score.

In parallel with the study of morphological characteristics of plants and biochemical properties of fruits, their ecological properties, namely, resistance to adverse biotic and abiotic

environmental factors, were investigated (Table 3). According to Table 3, the forms of checker tree are characterised by high resistance to pests, above average and increased winter hardiness, and high drought resistance, which is important in the case of introduction of these forms into the areas of unstable or insufficient moisture in Ukraine.

Table 3. Resistance of new forms of checker tree to adverse biotic and abiotic environmental factors

Factor	Form		
	Eva	Podolianochka	Slavka
pear leaf blister mite (<i>Eriophyes piri</i> Pagenst.), score (1-9)	8	8	9
rowan aphids (<i>Dentatus sorbi</i> Ralt.), score (1-9)	7	7	7
winter hardiness, according to S.Ya. Sokolova, points (1-8)	6 (above average, the top of annual shoots freezes)	6 (above average, the top of annual shoots freezes)	7.5 (the top of annual shoots rarely freezes)
drought resistance, according to S.S. Pyatnitsky, score (1-5)	4.5 (high, leaves lose their turgor during the day, wither, but restore it at night), for young plants – medium, 4 pt.		

Source: developed by the authors

According to the findings, the new forms seemed well adapted to the complex of weather and climatic factors of the northern forest-steppe of Ukraine, in particular, according to the results of overwintering, the average winter hardiness score was 2.5 points. The period of fruit fall. Long-term fruit ripening (1.5 months): beginning – 2nd ten days of August, end – late September. Fruits can remain on the tree until the first frost, and then gradually fall off. It was found that the phenophase of “budding” lasts from April 22 to May 5, and the phenophase of “flowering” takes place from May 8 to May 22. The duration of these phenophases is 18-28 days and depends on the temperature regime.

After the 2018 harvest year, in the following 2019-2021 years of research, checker tree slowly restores the fruiting energy.

For example, the “fruit ripening” phase in 2015 fell on August 5, and full fall ended on August 15, and in 2018, fruit ripening occurred on September 15, and mass fall – on September 28. In checker trees, this period varies by almost a month in different years. Under favourable weather conditions, the ripening period of fruits occurs in the 1st ten days of September; they are juicy and much larger, fall off completely after the first frost.

The average vegetation period is 216 days. The growth period of shoots lasts 143-189 days. Then the plant enters the dormant period, which lasts an average of 150 days.

The analysis and systematisation of the literature revealed that the species of checker tree (*Torminalis glaberrima* (Gand. Sennikov & Kurtto) is a forest, medicinal, fruit plant that belongs to a monotypic genus *Torminalis* Medik., family *Rosaceae*, and until recently its official name was *Sorbus torminalis* (L.) Crantz, first published in 1763 by the German botanist Heinrich Johann Nepomuk von Crantz, and until 2017 belonged to the genus *Sorbus*,

representing the section *Torminaria*. However, based on statements of A. Kurtto *et al.* (2018), species with simple leaves traditionally belong to the genus *Sorbus*, and as noted by E.Y.Y. Lo & M.J. Donoghue (2012) is considered to form a separate monophyletic group.

As noted by Y. Prokopuk *et al.* (2022), checker tree is one of the most valuable hardwoods in Europe, in particular *Torminalis glaberrima*, which has prospects in green landscape construction, including urban forestry, especially in regions with predicted edaphotope moisture deficiency. According to V. Sarv *et al.* (2020), checker tree fruits have a therapeutic effect, as they show high antioxidant activity due to the high content of phenolic and flavonoid compounds, tannins. Therefore, fruits have long been used to treat, including various inflammations, intestinal disorders, etc. According to A. Aytin *et al.* (2018), checker tree wood is fine-grained, very dense and has good flexural strength, it is used for the manufacture of various materials. In particular in the past, such wood was used for the manufacture of screws for wine presses, billiard tables, musical instruments, turning products, flutes, keys for pianos, organs, harpsichords and bagpipes, bases for measuring instruments, etc., since the wood of these plants does not expand or contract.

Based on an in-depth analysis of the theoretical material, L. Lanier *et al.* (1990) note that the range of checker trees covers certain territories of Ukraine (Podillia, Bukovina, Eastern Carpathian Foothills, Transcarpathia, Crimea), and other European countries (Great Britain, France, Italy, Switzerland, Austria, Czech Republic, Slovakia, Denmark, Germany, Poland, Romania, Hungary, Bulgaria, Moldova, Sakartvelo, etc.), in particular, which are located on the territory of the Balkans (Croatia, Montenegro, Bosnia and Herzegovina, North Macedonia, Albania, Greece) and the Pyrenees (Portugal, Spain) peninsulas, and in certain areas of West

Asia (Turkey, Iran, Azerbaijan, Armenia) and North-West Africa (Lebanon, Syria, Morocco, Algeria). Notably, this species was introduced to the territory of the United States of America, Washington state.

Torminalis glaberrima (Gand.) Sennikov & Kurtto includes two varieties: *Torminalis glaberrima* var. *torminalis* (range: Europe, north-western Africa) and *Torminalis glaberrima* var. *caucasica* (mountain ecosystems of the Caucasus and Elbrus). L.V. Markivska *et al.* (2020), quoting E.C. Gabrielyan, notes that in addition to the above-mentioned varieties, according to the degree of dissection of the leaf blade, there are also *Torminalis glaberrima* var. *pinnatifida*. Based on the morphological characteristics of fruits, L.V. Markivska *et al.* (2020), quoting M.I. Kosets, identifies 3 mutational forms, emphasising their ancient origin: *Sorbus torminalis* (L.) Crantz f. *genuiana* Kossetz, *S. torminalis* (L.) Crantz f. *intermedia* Kossetz and *S. torminalis* (L.) Crantz f. *dolichocarpa* Kossetz.

In Ukraine, checker tree is not subject to selective felling and is protected as a rare and valuable native species in the Dniester Canyon and Chernivtsi regional landscape parks, Karmeliukove Podillia and Podilski Tovtry national nature parks (NPP), Crimean, Karadazh, Yalta mountain and forest nature reserves, and Medobory (a protected area within the Pidvolochysk and Husiatyn districts of Ternopil Oblast), and protected areas of Vinnytsia, Ternopil, Ivano-Frankivsk, and Chernivtsi oblasts, have been listed in the Red Book of Ukraine since 2009 with the endangered status. Unlike in Ukraine, in France, the checker tree is not threatened with extinction and the International Union for Conservation of Nature (IUCN) classifies it as a species with a low risk of extinction, but locally it is considered vulnerable, in particular, in the Nord-Pas-de-Calais (former French region). In the forest ecosystems of south-western Germany, on behalf of the Federal Agency for

Agriculture and Food of this country, during 2010–2013, 80 thousand rare species of checker tree were registered, individual specimens, in particular near Blankenheim (North Rhine-Westphalia), acquired the status of natural monuments (Latté, 2021). In Poland, the checker tree has been under strict protection since 1946, is included in the Red List of this country and is almost threatened with extinction and is protected in such reserves as: Czerwona Róża, Brzęki, Białowodzka Góra, Wąwóz Lipa, Ustronie, etc. (Każmierczakowa *et al.*, 2016).

L. Willey (2020) reports that only 2% of the UK's territory is occupied by forests, so the preservation of seeds of ancient forest species-indicators, including checker tree (*Torminalis glaberrima*), is crucial.

According to M.C. Rivers & E. Beech (2017) internationally, checker tree is on the Global Red List and in the European Red List of Trees (Rivers) in the category of Least Concern (LC or LR/lc) (Rivers *et al.*, 2019). N.P. Schpak (2019) emphasises the importance of *in vitro* methods in combination with *ex situ* as a means of preserving and maintaining the level of stability of checker tree species.

Checker tree plants are mesomorphic, scleromorphic nanophanerophyte or phanerophyte can often be found in association with oak, beech, ash, hornbeam. Checker tree is distributed in the undergrowth of oak and beech forests, or ecotone between beech and oak forests, and in mountain oak forests. As noted by L.V. Markivska *et al.* (2020) and N.P. Schpak *et al.* (2020), for the renewal of checker trees, the taxation component of plantings includes up to 8 units of oak, 3 – hornbeam, 2 – ash, 1 – related species, including checker tree.

Young checker trees are not demanding for lighting and grow well in partial shade, unlike older plants. The fruit is a food base for many birds and some mammals, which makes the tree ecologically important. M. Kovanda (1992)

notes that the life span of checker tree exceeds 300 years, in particular, 280 and 300-year-old specimens were found in the Czech Republic (the town of Tišnov in the Brno-Venkov district of the South Moravian region and the town of Železná Ruda in the Klatovy district of the Plzeň region). According to Monumentaltrees (n.d.) on the territory of Austria (Brand-Laaben, Neulengbach, in the Vienna forest, as well as on the outskirts of the village of Kropfsdorf near the town of Michelbach, Lower Austria) there are several very tall trees over 25 m.

Checker tree *Torminalis glaberrima* is a deciduous tree up to 25 m (30 m) tall by biomorphology, with a trunk diameter of 15-75 cm (up to 1 m), and a growth rate of about 0.5 m during the growing season. Notably, in Germany, in particular in Hengstberg, east of Gross Lengden in the south of Lower Saxony, checker tree plants, which do not dominate in any forest group and are usually found individually or in groups, are 35 m high. The crown of checker trees is dense, narrow in habitus, and in individual specimens – wide. According to the shape of the top, they range from cone-shaped, semicircular, ovate, inversely ovate, elongated, rounded to opposite elliptical. The root system of plants is buried up to 3 m. Buds are yellow-green, yellow-olive, not pubescent, sticky, very small, small, medium and large in size, round-ovate, round-elongated in shape, and also characterised by different apices: blunt, rounded, and pointed. In addition, vegetative buds at the angle of placement relative to the shoot are very or slightly deviated, pressed. The leaves of plants are green, alternate, simple, about 20 cm long, up to 10 cm wide, palmate-lobed, and the blades at the top are pointed, their number is from 3 to 7. Inflorescence – corymb-shaped. The fruit is an apple up to 15 mm long, with a diameter of about 10 mm, the skin colour is light or dark brown, less often red-brown. According to reports of P.A. Thomas (2017), checker tree is

diploid ($2n=34$) or exclusively triploid ($2n=3x=51$), its plants are characterised by cross-pollination (alogamy), autogamy accounts for only about 1%. Due to cross-pollination, checker trees are characterised by xenogamy or pollination with transferred pollen from one flower to the stigma of the pistil of another flower of a particular plant, which, according to the authors (Moskalets *et al.*, 2020) is close to 75%. By hybridisation, checker tree develops diploid and polyploid hybrids with representatives of the genus *Aria* (Pellicer *et al.*, 2012), in particular, hybrids with mountain ash of the subgenus or genus *Aria* develops forms that belong to the genus *Karpatisorbus*, rowan trees of subgenera (or genera) *Aria* and *Sorbus* – forms belonging to the genus *Scandosorbus* (= *Borkhausenia*), with species of the genus *Malus* – hybrids that are allocated to the genus \times *Torminalis Holub*. According to K.P. Latté (2021) hybridisation between *Torminalis glaberrima* and different species from the genus *Aria* (in particular *Sorbusaria*) gave an opportunity to create species *Sorbus latifolia* and *Sorbus bristoliensis*. In addition, as evidenced by T. Rich *et al.* (2022), checker tree gave rise to numerous taxa in *Sorbus* nothosubgenus *Tormaria* Májovský & Bernátová, and several taxa in *Sorbus* nothosubgenus *Triparens* M. Lepší & T.C.G. Rich, and thus it is an important ancestral species.

In natural conditions, it is possible to select forms of checker tree with valuable economic characteristics that can be effectively used in the conditions of fruit, decorative gardening, forestry (Grynyk *et al.*, 2019). According to C.M. Piagnani *et al.* (2018) and V. Loewe-Muños *et al.* (2020) mixed plantings of checker tree with other species allow selecting specimens with the best wood quality.

Summing up the above, it can be noted that increasing the attention of the fruit and berry sector of agriculture and forestry to checker tree, and the search and selection of new ecological and adaptive forms for introduction into

the system of the ecological network has prospects and ecological importance for combining with the biocenotic link, preserving as a Red Book species in Ukraine.

Conclusions

New forms of checker tree – Eva (UN 0700091), Slavka (UN 0700090), and Podolianochka (UN 0700092) – were selected and studied. They were included in the Genetic Bank of Plants of Ukraine in 2022 by the National Centre for Plant Genetic Resources of Ukraine (Kharkiv).

Morphological studies have revealed a weak growth force of checker trees of the Eva, Slavka, and Podolianochka forms. It has been documented that the habitus of Eva is conical, that of Podolianochka – from straight to spreading, and that of Slavka is spreading. In the open area, various crown shapes are noted: in Eva – elongated, in Slavka – rounded, and in Podolianochka – transversely elliptical. New forms have strong branching. For the forms under study, the anthocyanin colour of the top of the young shoot is moderate, and the colour of the annual shoot is dark brown. Regarding vegetative buds, differences are found in the shape of the tip: Eva – pointed, Podolianochka – blunt, Slavka – rounded. The size of vegetative buds varied, but all forms are characterised by their pressing. Morphological differences in the leaves were found to be insignificant: the density of placement, length, width of the leaves – average, green colour – moderate, cross-sectional profile shape – straight or slightly concave, anthocyanin colour – weak or absent.

As for the morphological characteristics of the flower, it was noted that the pedicel is long (1.5–2 mm), the colour of the anther is yellow and orange, the petal shape is rounded, the pistil stigmas are lower than the anther height, i.e., heterostylic or equipetal, which leads to better contact of insects with pollen during nectar collection.

It is worth noting that the new forms of checker trees are not characterised by uniform ripening of elliptical fruits. If the size of the fruit for the Eva and Podolianochka forms is large, then for Slavka it is very large. However, the Slavka form is distinguished by its greater weight and aroma.

It was found that the elements of originality of the Slavka form are a feature of the crown shape (cup-shaped), which determines the level of productivity, low growth force (0.25 m/vegetation), good tolerance of pruning (which affects the size and yield of fruits), increased fruit weight (1.9 g), high number of fruits on the stem (≥ 20), pleasant and harmonious taste of fruits, lack of periodicity in fruiting in nature and in culture, high self-fruitfulness (75%), increased yield of fruits from the plant (> 15 kg/plant), by year (5 t/ha), increased winter hardiness (7.5 pt.), high drought resistance (8 pt.), high resistance to pear leaf blister mite (9 pt.). Elements of originality of the Podolianochka form are the average growth force (0.25 m/vegetation), high degree of flowering (70%), uniform ripening of fruits in culture, high fruit weight (1.8 g), average ripeness group, increased content of ascorbic acid in fruits. It was found out that the elements of originality of the Eva form are high plasticity in terms of pruning, increased fruit weight (2.1 g), large size of fruits (fruit diameter – 2.2 cm), high degree of flowering (60–80%), increased self-fertility (69%), increased content of ascorbic acid (55 mg/100 g of raw weight), high tasting score of fruits (5 pt.), above average winter and increased drought resistance, early time of maximum fruiting in culture (on the 3rd year), increased fruit yield from the plant (12.5 kg).

Further research may be devoted to ensuring the successful survival of selected forms of checker trees in new conditions.

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Conflict of Interest

None.

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Еколого-біологічні особливості відібраних форм береки лікарської для успішної адресної інтродукції та реінтродукції в екомережу України

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Анотація. В статті розглянуто проблематику щодо інтродукції і реінтродукції червонокнижного виду береки лікарської в систему декоративного садівництва та лісозахисних і лісових екосистем. Саме тому метою роботи було провести моніторинг зелених коридорів сільських і міських екосистем лісостепової зони України, дослідити та відібрати кращі за морфологічними ознаками і фізіологічними властивостями форми береки лікарської для перспективних напрямів поширення і збереження у вигляді чистих і мішаних насаджень. У наукових дослідженнях застосовано такі методи: маршрутний, польовий, біометричний, лабораторний, порівняльного аналізу, математично-статистичний. В процесі виконання роботи інтродуковано, вивчено в умовах *in situ* та *ex situ* та відібрано нові форми береки лікарської для перспектив подальшої їх інтродукції та реінтродукції в екомережу України та збереження для активації трофічних, форичних та інших типів біотичних взаємодій в єдиній територіальній екосистемі. У зоні зелених коридорів сільських і міських екосистем лісостепової зони України виявлено малопоширені біотиби *Torminalis glaberrima* (Gand.)

Sennikov & Kurtto f. *Intermedia* Kossetz. Деякі екземпляри цих біотипів визначено як цінний матеріал для введення в систему плодового і декоративного садівництва, включаючи парки-пам'ятки садово-паркового мистецтва, а також пам'ятники природи, заповідні урочища, заказники і заповідники чистих і мішаних насаджень, алеї, лісомеліоративні смуги, тощо. Встановлено, що елементами новизни відібраних форм береки лікарської Єва, Подоляночка і Славка є особливість форми крони, яка визначає рівень продуктивності, мала і середня сила росту, нормальна реакція на формуючу обрізку (що впливає на крупність і урожайність плодів), висока ступінь цвітіння (60-80 %), крупно плідність (діаметр плоду понад 2 см), підвищена маса плоду (1,8-2,1 г), висока кількість плодів на суплідді (≥ 20 шт.), приємно-гармонійний смак плодів, висока якість плодів, відсутність періодичності в плодоношення в природі і в культурі, висока ксеногамія (69-75 %), висока урожайність плодів з рослини, підвищена зимостійкість (7,5 б.), висока посухостійкість (8 б.) і стійкість до шкідників, у т. ч. грушевого кліщика (7-9 б.). Результати досліджень можуть бути використані в перспективі поповнення чистих і мішаних насаджень екологічної мережі України

Ключові слова: *Torminalis glaberrima* (Gand.) Sennikov & Kurttof. *Intermedia* Kossetz.; біохімічні властивості; нові біотипи; поповнення екологічної мережі; червонокнижний вид; вміст аскорбінової кислоти

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Ecosystem services of forests and their economic valuation: Prospects for sustainable development

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Abstract. The relevance of the topic is justified by the diversity of unique natural ecosystem objects in the territories of Kosovo and North Macedonia, where forestry activities are traditional. The aim of the study is to analyse the current state of ecosystem services provided by forests in Kosovo and North Macedonia in the context of their assessment and development prospects. Several general scientific empirical and theoretical research methods were employed, including comparison, generalization, analysis, synthesis, and abstract-logical methods. The article characterizes the current state of forest resource utilization in Kosovo and North Macedonia, highlighting key issues in the management of forest lands, including those hindering the development of ecosystem

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services. The study justifies indicators of the level of forest resource utilization in Kosovo and North Macedonia, examining the percentage ratio of forest cover indicators in the Western Balkan countries. The relationship between land areas of different categories and purposes in Kosovo is analysed, along with the designation of protected areas within forested areas in North Macedonia. The necessity of conducting an economic assessment of specific ecosystem services provided by forests is justified. Six methods used in the economic valuation of natural goods resulting from forest resource utilization are detailed, deemed most suitable for the Western Balkan countries. A comprehensive list of the most relevant functions of forests requiring economic assessment is compiled. Throughout the justification of all stages of the work, specific ecosystem services provided by forests that may gain greater importance in the future are identified. The practical significance of the study lies in forming the fundamental methodological aspects that can be utilized in the assessment of ecosystem services provided by forests

Keywords: natural forest complexes; Western Balkans; euro integration; climate change; qualitative and quantitative indicators

Introduction

Within the framework of the processes of rapid European integration, the policies of the Western Balkan countries aim to address environmental issues and conservation of natural resources in accordance with the norms and standards of the European Union related to standards for forest management, biodiversity conservation, forest fire control, and conservation of effective ecosystem forest services. Kosovo and North Macedonia, as countries with relatively unstable socio-economic development indicators, especially Kosovo with its precarious political situation, are obligated to incorporate the principles of the European Green Deal (2023) for the preservation of surrounding ecosystems and forest resources into their development strategies.

The issue of the insufficient balance in the functioning of ecosystem services provided by forests has become significantly more acute in Kosovo in recent times due to various factors. Over the past few years, forested areas have been excessively exploited and logged, primarily to meet the heating needs of the local population. Additionally, there is a lack of effective mechanisms for managing forest resources, and

comprehensive programs for the development and protection of forested areas at the national level are nearly non-existent. If such programs do exist, they often involve tasks that are challenging to implement, while regulatory acts are not adapted to modern conditions and the needs of the forestry sector in the context of climate, hydrological problems, and soil degradation.

It is worth noting, that in North Macedonia, other problems related to the insufficient provision of ecosystem services by forests include illegal logging, the use of forested areas for other purposes, pollution with harmful substances due to anthropogenic activities, and the impact of other negative factors resulting from rapid urbanization. Loss of forest cover and low efficiency in forest regeneration are also notable issues. Forest resources have always held a fundamental place in the overall state system of the Western Balkans region. Therefore, it is essential to conduct an economic assessment of ecosystem services provided by forest resources. This serves as a crucial tool for ensuring sustainable forest management and the preservation of their natural capital. Such an assessment

plays a role in justifying the value of ecosystem services and evaluating the economic indicators of the indirect services of forests, such as climate regulation, soil moisture conservation, and others, which are inherently challenging to measure (Tykhonova *et al.*, 2021).

F. Humolli *et al.* (2023) consider the utilization of Kosovo's forest resources within the context of its significant physical-geographical and tourist potential. The prevalence of extensive forested areas, nature conservation lands, and the diversity of biota, unique landscapes, and flora characterize the natural ecosystems of the country as an important recreational and tourist asset. In this context, references to forest protection directions and the designation of lands for recreational and nature conservation purposes are crucial. The creation of a database of nature conservation objects, forest inventory, and the formation of a tourism management system are possible through the application of effective qualitative and quantitative analysis methods.

Scholars A. Bajraktari *et al.* (2020) examine the advantages of Kosovo's territorial location at the centre of the Balkans concerning economic opportunities based on the use of natural resources, particularly forests. The authors note that the creation of new borders and trade restrictions between Kosovo and neighbouring countries following the breakup of Yugoslavia has changed the quantity and type of available timber. Despite political or economic factors, the forest and wood processing industry in Kosovo remains a crucial element of the national economy with potential for further development.

D. Sanchez *et al.* (2023) conduct an environmental assessment of Kosovo in the context of the negative problem of climate change using Google Earth Engine tools. One of the main elements in the research structure is the creation of a large-scale deforestation model over the last few years. This allows for the analysis of the temporal function and the determination of

changes that have occurred for specific ecosystem services of the forest, such as reforestation speed and timber reserves.

A. Sertolli *et al.* (2023) examine the features of the functioning of natural forest complexes in the context of utilizing forestry waste for renewable energy purposes in Kosovo. The research results also highlight that Kosovo's forests currently provide an exceptionally high potential as a source of energy from biomass. This type of utilization of forest resources aligns with the directions of the European Green Deal initiative and the development of quality indicators for forest ecosystem services. Explorers Q. Ramshaj *et al.* (2021) conduct a detailed analysis of the current state of biodiversity in the natural forest complexes of Kosovo. The research reveals that many plant species are under the threat of extinction. Therefore, it is crucial to preserve and restore a wide range of different tree species, plants, animals, and microorganisms that interact with each other, creating ecological connections that contribute to maintaining balance in the system.

However, the issues of balanced use of forest resources in Kosovo and North Macedonia are not fully explored in the scientific literature, despite the unique natural ecosystems and landscapes of these countries and their significant socio-economic potential for the full revival of the forest industry and the provision of high-quality ecosystem services. The aim of the article is to substantiate the main reasons for the disruption of the cycle of effective forest ecosystem services in the territory of Kosovo and Northern Macedonia, and to identify areas of improvement in the utilisation of forest resources through modern methods of economic valuation of forest ecosystem services.

Materials and Methods

The information base of the research was the data from the International Monetary Fund

report on “Mitigation and Adaptation Challenges: How RSF (Resilience and Sustainability Facility) reform measures are aligned with the Green Agenda for the Western Balkans” (Republic of Kosovo..., 2023), which dealt with government policies and commitments from Kosovo regarding climate change, adaptation, and prioritization of the forestry sector to enhance environmental sustainability. According to the report formed by the representatives of the Economic Commission for Europe, the Food and Agriculture Organization of the United Nations, the Committee on Forests and Forest Industries and the European Forestry Commission on Forestry activities of the FAO Regional Office for Europe and Central Asia (2021), the report analysed the forestry activities of the FAO Regional Office for Europe and Central Asia analysed the current state of forest resources use in the territory of Kosovo and Northern Macedonia. Based on the Berlin initiative and the standing working group of the Regional Rural Development in South Eastern Europe (SWG) and their report Supporting the Regional Expert Working Group on Sustainable Forest Management in the Western Balkan Region (2022), the current state of forest management in Northern Macedonia and Kosovo was substantiated, in particular the ecosystem services of the forests of these countries were analysed in detail, as well as the main challenges currently existing in the field of forest management.

The scientific research was based on economic laws (law of self-interest, law of supply and demand) (Adam Smith Project, 2023), ecological laws (laws of biodiversity, climate change, toxic and hazardous substances, land, and water) (International Environmental Law..., 2017), their concepts and categories, as well as the main policy directions of European Green DEAL initiatives and modern geographical theories. The results of the work were substantiated by analysing the problem of

declining indicators of forest ecosystem services and comparing the territorial development of natural forest complexes of two countries of the same historical and geographical region.

As a methodological basis, the general scientific methods of research were applied:

- method of analysis to substantiate the ratio of forest cover characteristics on the terrain of the Western Balkan states; characterization of the ratio of land area of different categories and purpose on the territory of Kosovo; description of the ratio of protected areas within forest areas on the territory of Northern Macedonia; formation of the main methodological aspects that can be used in the assessment of forest ecosystem services;

- synthesis method for studying the peculiarities of forest natural complex functioning in its integrity and mutual connection of its parts on the territory of Kosovo and Northern Macedonia, with the establishment of current problems of full utilization of forest ecosystem services;

- comparison method to characterize the current quantitative and qualitative indicators of forest lands on the territory of Kosovo and Northern Macedonia; substantiation of the problems of forest resources use affecting the quality of forest ecosystem services on the territory of Kosovo and Northern Macedonia;

- generalization method to justify the need for economic valuation of specific forest ecosystem services; presentation of methods used in the economic valuation of forest ecosystem services; in the context of economic, social and environmental aspects, further research directions in the field of prospective sustainable development of forest ecosystem services in the territory of Kosovo and Northern Macedonia were justified;

- abstract-logical method to clarify the essence of the main concepts, definitions, and categories in the field of forest ecosystem services and their economic valuation, as well as in generalizing and drawing conclusions.

During the study, the provisions of the international treaty aimed at preserving biological diversity – Convention on Biological Diversity (1992) and the norms of the Convention on the Regulation of International Trade in Endangered Species of Wild Fauna and Flora (CITES) (1973) were considered.

Results

The area occupied by forest resources is defined as a land plot with crown cover of trees of different species, or of the same type more than 10% and an area of more than 0.5 ha, where trees are able to reach a minimum height of 5 m and a maximum height of more than 100 m (Republic of Kosovo..., 2023). Forest resources are an important component of nature that includes various elements that can be utilized for different needs.

The ecosystem services of forests represent various useful functions and benefits that forests provide to people and other elements of the ecosystem. These services can be direct or indirect benefits, and they fulfil various ecological, economic, and social functions. Supply of wood and other forest products – the use of wood for construction, furniture, sports equipment, and musical instruments. Other forest products are needed for the food and medical industries. Water regulation – forest management plays an important role in water conservation and

filtration, regulating water flows and ensuring water quality for different ecosystems and users. Climate regulation – trees absorb carbon dioxide, produce oxygen and influence the climate, which is important to combat climate change. Soil conservation – forest complexes help prevent soil erosion, preserve soil fertility, and improve soil morphological structure. Biodiversity – forest complexes promote the growth and maintenance of a large variety of plant, animal, and microorganism species (Zeki Baškent, 2021; Dashtbozorgi *et al.*, 2023). Recreational opportunities – areas occupied by forests serve as places for tourism, recreation, sports, and other recreational activities, which affect people's physical and mental health. Cultural heritage – some forest areas are natural monuments with a centuries-old history reflecting the culture and traditions of a region or country. For a full economic valuation of forest ecosystem services, the current advantages and disadvantages of forest natural complexes as a whole should be analysed.

Forest cover varies across the western countries of the Balkan region. The largest forest area is characterized by Bosnia and Herzegovina. At the same time, the countries presented in this study, namely Kosovo and North Macedonia, occupy the median forest cover in the overall ranking of countries in the Western Balkans (Fig. 1).

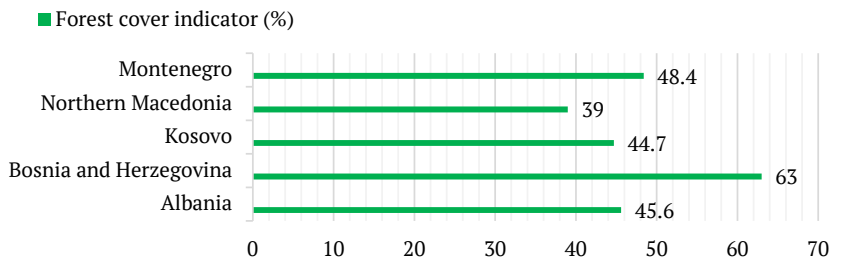


Figure 1. Percentage of forest cover in the countries of Western Balkans

Source: developed by the authors based on source data Forestry activities of the FAO Regional Office for Europe and Central Asia (2021)

It is important to note that the national policy directions for the effective management of forest resources are provided by the relevant executive authorities. For example, on the territory of Kosovo there is the Ministry of Agriculture, Forestry and Rural Development, which is subordinated to a separate executive body, the Forestry Agency. At the same time, in Northern Macedonia there is a sector of forestry and hunting, the peculiarity of this country is that the control over the lawful use of forest resources is carried out thanks to the Forest

Police, which has responsibilities for the protection of forests in accordance with the Forest Law (2009) and is part of the Ministry of Agriculture, Forestry and Water Management (Sustainable Forest Management..., 2022).

The largest inventory of forests on the territory of Kosovo was conducted in 2012 and at that time the forest area was 481 thousand ha, respectively about 50% of the country's total area (Fig. 2). Since 2012 until now, changes in the forest area have been continuously monitored.

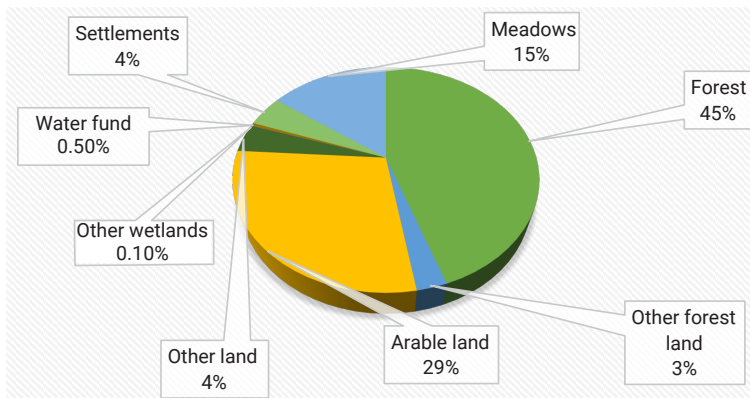


Figure 2. Percentage of land area of different categories and intended use in Kosovo

Source: developed by the authors based on source data Forestry activities of the FAO Regional Office for Europe and Central Asia (2021)

Since 2018, the implementation of the “National Forestry and Reforestation Programme of Kosovo”, which will run until 2027, as well as the National Forest Health Programme (NFHP) 2018-2027 is taking place on the territory of Kosovo. The main objectives of these programmes are to increase the forest area by 5%. However, according to experts' assessments, these programmes contain rather complicated plans for implementation, as there is currently a shortage of highly qualified specialists in the forestry sector. In particular, insufficient funding of the programme also limits the implementation of its main goal. The main problems

inhibiting the quality ecosystem services of forests in Kosovo are (Veselaj & Mustafa, 2015; Nichiforel *et al.*, 2021):

- more than 10% of the forest area is negatively affected by biotic and abiotic agents, which resulted in damage of 5.8 million m³ of trees;
- forest fires, which occur in most cases due to the negligence of forest visitors or farmers, disturb forest areas in more than 12 thousand ha of the total forest area;
- cattle grazing causes mechanical damage to forestry lands on about 2 thousand ha of the total forest area;

- unfavourable weather conditions and climatic factors, such as drought and frost, affect the qualitative and quantitative properties of forests.

According to the latest forest inventory data, 40% of public forests and 29% of private forests in Kosovo are subject to uncontrolled or illegal logging. This situation is caused by the low socio-economic standard of living of rural inhabitants. At the same time, large amounts of forest residues are often left in the forest after logging, causing loss of forest fibre, increased insect pests and increased risk of forest fires (Sustainable Forest Management..., 2022). Soil degradation, in particular erosion inherent in mountainous areas, is the cause of decreasing quantitative indicators of forest resources, disturbing the integrity of surrounding ecosystems and reducing biodiversity.

Private forest owners do not currently produce quality forest management plans. Currently, the average private ownership of forest land is about 1.5 ha. As for Northern Macedonia, compared to Kosovo, the country has twice as much land area and forest natural complexes cover about 1 million ha, which is also twice as much. Accordingly, the forest area in Northern

Macedonia accounts for 40% of the country's territory (Ramshaj *et al.*, 2021). Currently, the functioning of the forestry sector in Northern Macedonia is regulated by a few regulations, the most important of which is the document "Strategy for Sustainable Development of Forestry 2006-2026" (Sustainable Forest Management..., 2022). The key objectives of this Strategy are: balanced development of forest lands; protection of natural forest complexes, biodiversity; control of changing climatic conditions; implementation of effective mechanisms against soil degradation and desertification; effective spatial planning.

The main monitoring and evaluation of forest ecosystem services is carried out by the state enterprise "National Forests" and institutions for the management of protected areas. It is important to note that conservation and forest management in the territory of Northern Macedonia are identical concepts, which have a special role and importance. Thus, according to the intended purpose, more than 140 thousand ha of the total forest land area are special purpose forests, which include objects of national parks and multifunctional areas, as well as objects of natural reserve fund (Fig. 3).

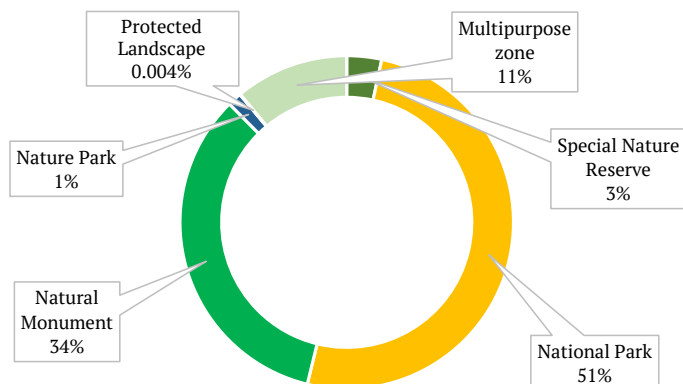


Figure 3. Percentage of protected areas within forested areas in North Macedonia

Source: developed by the authors based on source data Forestry activities of the FAO Regional Office for Europe and Central Asia (2021)

Private ownership dominates 11 per cent of the country's total forest land area, most of which is held by individuals or legal entities. It is important to note that private owners initiated the creation of the National Association of Private Forest Landowners (NAPFO). This organization has more than 200 forest management units in its membership, and is also engaged in the development of forest management plans, which are formed and improved every 10 years (Pérez-Sánchez *et al.*, 2021; Morgan *et al.*, 2022). It is also a positive practice that the country's leadership is trying to improve the level of training of forestry specialists by creating special school classes of forestry and landscape architecture. Such classes are currently established in 2 general education schools, and the Faculty of Forestry at the University of St Cyril and Methodius in Skopje is the highest institution for training forestry and landscape architecture specialists (Sustainable Forest Management..., 2022).

Even though the policy of North Macedonia aims to preserve the ecosystem services

of forests at the heart of which solutions for reducing the risks of natural disasters, forest fires and ensuring hydrological balance, balanced land management in mountain landscapes, still some problems can be highlighted: insufficiently regulated legislative framework; lack of a complete, updated inventory of forest lands; lack of up-to-date indicators of quantitative and qualitative characteristics of forests; increase in the risk of forest degradation and forest degradation in the mountain landscapes. Forest ecosystem services cover a wide range of benefits and services provided to society, the economy, and the environment. Considering the characteristic features of the functioning of the forestry sector on the territory of Northern Macedonia and Kosovo, it will be relevant for these countries to conduct an economic valuation of specific forest ecosystem services (Table 1).

The economic valuation of forest ecosystem services is a complex process involving different methodologies and approaches (Fig. 4).

Table 1. Features of the economic assessment of forest ecosystem services in Kosovo and North Macedonia

Forest ecosystem service	Features of evaluation
Water conservation	Forests act as natural filters that improve water quality. The assessment may include measuring reductions in water treatment costs.
Biodiversity	Woodlands are home to many species of plants and animals. Biodiversity valuations may include the cost of conserving unique species and their genetic material.
Mitigating climate change	Trees absorb carbon dioxide, which mitigates the effects of climate change. Assessment may include measuring reduction in cost of climate disasters.
Recreational opportunities	Forests provide places for rest and recreation. However, economic assessment may include measuring profits from tourism and active recreation.
Provision of timber and non-timber products	Forests are a source of building materials, wood, cellulose, medicinal plants and other products. The assessment describes the market price of these materials.

Source: developed by the authors according to source Forestry activities of the FAO Regional Office for Europe and Central Asia (2021)

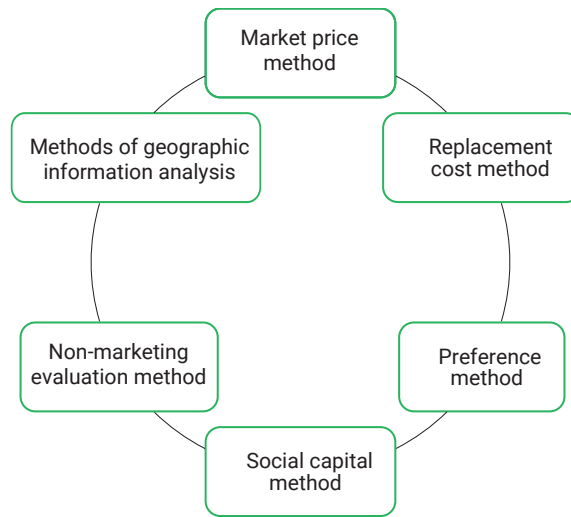


Figure 4. Methods used in economic valuation of forest ecosystem services

Source: developed by the authors

Thus, the economic valuation of forest ecosystem services aims to determine the value and importance of the various benefits and forest ecosystem services. Figure 4 presents six best-practice methods for economic valuation of forest ecosystem services for the territory of Kosovo and North Macedonia. The market price method is based on existing market prices of forest products and services, such as timber, forest products, tourism, and recreation. This method is applicable to those services that have direct commercial value. The replacement cost method calculates the replacement costs of ecosystem services, for example, if water or soil values are lost due to deforestation. The costs of restoring or creating alternative systems can serve as a basis for valuation. The preference method measures people's willingness to pay to conserve or restore ecosystem services. It can involve various survey and analysis techniques, such as contingent analysis, in which interviewees express their willingness to pay for certain benefits.

The social capital method compares changes in social capital (e.g. health, education, safety) before and after changes in forest ecosystems. This method seeks to link ecosystem services to societal well-being and living standards. The non-market valuation method has no obvious market analogue, in the context of climate regulation, biodiversity maintenance, aesthetic values. Various methods are used here, including expert judgement and life cycle value methods. Geo-information analysis methods rely on the use of geospatial data to assess and mapping ecosystem services, which can include estimating soil coverage, changes in vegetation, water quality and other parameters (Crivellaro *et al.*, 2021).

The assessment of forest ecosystem services is a complex and multidimensional process that involves analysing various aspects such as biodiversity, climate regulation, water resources and others. The main aspects of the methodology that can be used in the assessment of forest ecosystem services in the territory of Kosovo and Northern Macedonia are summarized in Table 2.

Table 2. Characteristics of the main methodological aspects that can be used in assessing forest ecosystem services

Methodological aspects	Characteristic
Identification and classification of services	Identification of various ecosystem services of forests. This may include services related to timber, water, climate, biodiversity, recreation and other aspects.
Quantification	Measuring or estimating the quantities and characteristics associated with the provision of ecosystem services. For example, volume of wood, amount of carbon, species diversity.
Selection of assessment methods	Selection of assessment methodology depending on specific services and data availability. Various methods may include economic methods, geographic information analysis, biophysical modelling.
Valuation of non-market services	For services that do not have direct market equivalents (e.g. climate regulation, maintaining biodiversity), use methods such as contingent analysis or preference methods to measure people's willingness to pay for these services.
Data Integration	Integrate results from different sources and valuation methods to form an overall picture of the value of ecosystem services.
Time frame	Accounting for temporary changes in the provision of ecosystem services and their values. This may include analysing trends and predicting future changes.
Stakeholder involvement	Involving stakeholders in the assessment process, such as local communities, businesses, and government agencies. This will help to accommodate different points of view and needs.
Results report	Generating reports describing methodology, data, results, and conclusions. Documenting all methodology and data used is important for transparency and reusability.
Update and adjustment	Regularly update assessments to reflect changes in forest conditions, including due to climate change, human impacts and other factors.

Source: developed by the authors

The future of forest ecosystem services depends on several factors such as climate change, technological advances, social and economic transformations. However, some forest ecosystem services may become more important in the future, in particular: carbon storage and offsetting services may become more popular due to increasing attention to climate change (Weiss *et al.*, 2019). Forests can be used to produce carbon credits and other emission reduction instruments. Forests are major sources of biodiversity, and services related to conserving the gene pool of forest species and maintaining biodiversity may increase

in importance in the future. Some forest species may contain various bioactive substances with medicinal properties. The development of forest medicine as a separate branch and biopharmacy may bring out new possibilities for medical utilization of forest resources. The use of modern technologies such as satellite data, drones and artificial intelligence can improve forest management to optimize the supply of various ecosystem services.

Discussion

Forest ecosystem services play a key role in ensuring the stability of natural ecosystems and

human well-being. The economic valuation of these services is important for sustainable development and efficient environmental management. Forests provide a wide range of ecosystem services, including purifying air and water, supporting biodiversity, regulating climate, supplying timber for industrial purposes, and providing raw materials for pharmaceuticals and nutrition. Assessing the economic value of these services helps to understand their importance to the economy and society. Forests provide recreation and leisure areas, improving people's physical and mental health. In doing so, economic valuation helps to account for these positive impacts on quality of life. The ecosystem services of forests act as natural barriers, protecting against landslides, floods, and other natural disasters (Osanova *et al.*, 2021). Economic valuation incentivizes the development of sustainable forestry practices, balancing timber extraction with the preservation of ecosystem functions. Justifying the total return from forestry operations to the national economic system helps in determining optimal natural resource management strategies and managing the risks associated with the loss of ecosystem services.

X. Naime *et al.* (2020) from Norway and Mexico explore the characteristics of natural regeneration of secondary forests as an important source for the provision of forest ecosystem services to meet consumer needs. The authors also note that balanced land management is also critical for climate change mitigation. However, to maximize natural regeneration, synergies between different types of forest ecosystem services and consumers need to be established. In doing so, scientists recommend applying economic valuation of forest ecosystem services through contingent valuation and direct market value methods. Such a method is appropriate for determining the stocks of wood and carbon sinks in young and secondary

forests. As a result of the study, it was possible to establish that for consumers or landowners it would be more economically efficient to naturally regenerate older forest areas because young secondary forests are valued for the future, not for the present. Natural regeneration of forests is the key to the provision of all other services and goods resulting from forest management (Onopriienko *et al.*, 2023). It is worth agreeing with the fact that balanced management and rational utilization of forest resources is the key to a faster recovery of the qualitative and quantitative properties of forests. This study notes the extraordinary role of forests in preventing active climate change, but does not detail the processes of natural forest regeneration.

D. Saha & A. Taron (2023) from India and Sri Lanka explore the general concept of forest natural complexes ecosystem and their importance for maintaining sustainable ecological and economic development of the country. The forest ecosystem is fundamental to economic-ecological permanence. India is home to the largest forest complex on planet earth, the Sundarbans. It is this complex that provides numerous ecosystem services to the forest dwellers and the local rural population. In this study, scientists used the non-market valuation or contingent valuation method to determine the personal contribution that the population is willing to make to accelerate the natural regeneration processes of the forest. Currently, consumers are willing to forego excessive cutting of timber or obtaining other forest products during active forestry activities (Ivanova *et al.*, 2023). This position of the population allows the largest forest area on the planet to have a perspective of development and future. The present study confirms the importance of the results of the work from India and Sri Lanka because the key role in the conservation of natural resources, in particular natural forest complexes, is played by human consciousness

and understanding of the fact that the present requires the population of the planet Earth to understand the significant damage from excessive anthropogenic pressure. In this analysis, the authors present information revealing the problem of rather uncontrolled deforestation in both Kosovo and Northern Macedonia. Large-scale forest fires are not uncommon as a result of farmers' activities in Kosovo.

K. Shrestha *et al.* (2023) from Nepal and Switzerland note the importance of research on the features of biodiversity as an important ecosystem service of forests in the territories of the Far Eastern Himalayas. The paper finds that most of the studies conducted recently have analysed the quantity of timber reserves, water use patterns, and recreational services. Only 15% of all studies focus on biophysical characterization and assessment of socio-cultural aspects. The authors also advise that during the study of ecosystems, their forest services should be considered in an integrated manner, rather than individual components of natural forest complexes. In doing so, the causes and issues that influenced the disruption of the overall ecosystem cycle should be justified. This paper shares the importance of research in the context of an integrated study of all ecosystem services, at least a brief analysis of them to enable the formation of an overall system, as each country will have its specificities, considering climatic, resource, socio-economic and political aspects. In the present study results, experts note that a full economic valuation of the use of forest resources and the provision of related ecosystem services requires an analysis of current advantages and disadvantages in the functioning of forest natural complexes as a whole.

F.A. Taye *et al.* (2021) from Denmark and Australia consider the importance of meta-analyses of the economic value of global forest ecosystem services in the context of an effective tool for understanding and assessing the

contribution of forests to the economy and the overall well-being of society. Such analyses systematize and synthesize existing economic research and data aimed at determining the value of the diverse ecosystem services that forests provide. The value of conserving the unique plant and animal species that exist in forests can be determined based on the value to science, the potential medicinal or biotechnological value of some species (Skliar *et al.*, 2020). Forests influence atmospheric composition by deepening carbon and providing other climate services. The value of services can be determined in the context of reducing greenhouse gas emissions and building climate resilience. Forests offer places for recreation, tourism, and other recreational activities. The value of this service can be determined through the tourism industry and other ways of spending time in forests (Hrynyk *et al.*, 2023). Meta-analyses can help to establish an overall picture of the economic value of forest ecosystem services and their impact on the sustainable development of society. It is also important to consider social and environmental aspects when considering the value of forests to society. In the current results of the study, the authors partially analysed forest natural complexes, considering their contribution to the national economic system.

In summary, the forest ecosystem services and other natural complexes not only sustain nature, but are critical to sustainable development and human well-being. Conservation and sustainable management of ecosystems are key to safeguarding these important services for future generations. For example, forests are an important element of ecological resilience, facilitating adaptation to changes in the natural environment and the robust functioning of ecosystems. Trees and vegetation keep the soil layer from degradation processes and prevent erosion. This helps maintain soil fertility

and prevents pollution of water bodies. Forests create natural landscapes that are attractive for recreation, tourism and leisure, contributing to the physical and mental health of people.

Conclusions

Forest ecosystem services are the diverse benefits and functions that forests provide to the environment, society, and the economy. They include aspects such as climate regulation, water harvesting and filtration, biodiversity, provision of timber, honey, and medicinal plants, as well as recreational and cultural values. These services play a key role in sustainable development, maintaining the ecological balance and well-being of countries, regions.

Despite numerous challenges, the ecosystem services of forests in the territory of Kosovo and Northern Macedonia are a significant source of economic potential. An effective forest management policy can be the first step in achieving the desired high income from the forest industry in the system of national economy, as well as sustainable future development of forest ecosystem services. Due to the unique configuration of relief on the territory of the Western Balkans, the identity of geological and pedological composition and climatic conditions, it is possible to develop ecotourism in Kosovo and Northern Macedonia, which will involve forest areas as a territorial basis for the provision of this ecosystem service. At the same time, the preservation of the qualitative and quantitative properties of forest lands in these countries plays a considerable role in

the socio-economic development of rural areas. In this case, the consumer demand of the population can be provided with various ecosystem services of forests, in particular, the use of wood, technical, medicinal, and other forest products.

Sustainable development of forest ecosystem services is a key aspect of ensuring the ecological balance and well-being of society and requires a comprehensive and integrated approach that considers economic, social and environmental requirements. In particular, further research directions in the field of prospective sustainable development of forest ecosystem services could be: integration of forest ecosystem services into regional and local development strategies; developing financial instruments such as carbon credit markets to create economic incentives for the conservation and restoration of forest ecosystem services; building collaborative work with local communities, forest owners, businesses, and government will promote a balanced approach to managing forest ecosystem services; designing green infrastructure based on forest ecosystem services; development and implementation of effective legal mechanisms is a key factor in ensuring the sustainable development of forest ecosystem services.

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Conflict of Interest

None.

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Екосистемні послуги лісів та їх економічна оцінка: перспективи сталого розвитку

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Анотація. Актуальність теми зумовлена різноманіттям унікальних природних екосистемних об'єктів на територіях Косово та Північної Македонії, де лісогосподарська діяльність є традиційною. Метою дослідження є аналіз сучасного стану екосистемних послуг, що надаються лісами в Косово та Північній Македонії, в контексті їх оцінки та перспектив розвитку. Використано низку загальнонаукових емпіричних і теоретичних методів дослідження, зокрема порівняння, узагальнення, аналіз, синтез, абстрактно-логічний метод. У статті охарактеризовано сучасний стан використання лісових ресурсів у Косово

та Північній Македонії, виокремлено ключові проблеми в управлінні лісовими землями, зокрема ті, що перешкоджають розвитку екосистемних послуг. У дослідженні обґрунтовано показники рівня використання лісових ресурсів у Косово та Північній Македонії на основі аналізу відсоткового співвідношення показників лісистості в країнах Західних Балкан. Проаналізовано співвідношення між земельними площами різних категорій та цільового призначення в Косово, а також виділення природоохоронних територій у межах лісових масивів у Північній Македонії. Обґрунтовано необхідність проведення економічної оцінки конкретних екосистемних послуг, що надаються лісами. Детально описано шість методів економічної оцінки природних благ, отриманих в результаті використання лісових ресурсів, які вважаються найбільш придатними для країн Західних Балкан. Складено вичерпний перелік найбільш важливих функцій лісів, які потребують економічної оцінки. В ході обґрунтування всіх етапів роботи визначено специфічні екосистемні послуги, що надаються лісами, які можуть набути більшого значення в майбутньому. Практичне значення дослідження полягає у формуванні фундаментальних методологічних аспектів, які можуть бути використані при оцінці екосистемних послуг, що надаються лісами

Ключові слова: природні лісові комплекси; Західні Балкани; євроінтеграція; зміна клімату; якісні та кількісні показники

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Assessment of carbon emissions due to landscape fires in Ukraine during war in 2022

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Abstract. The Russian military aggression and the related socio-economic and environmental consequences have significantly affected the climate and production of ecosystem services through damage to forests, ecosystems, landscape fires and emissions of gases into the atmosphere. The study aims to estimate carbon dioxide emissions due to landscape fires in Ukraine during the year 2022. The OroraTech wildfire monitoring technology was used to detect fires, while perimeters of burned areas were delineated with Sentinel 2 time series. The Copernicus Dynamic Land Cover map was used to extract burned land covers. Emissions were calculated based on the intensity of fires (dNBR) with the share of burned biomass in different types of land cover. Biomass models were selected considering the dominant tree species within a specific region and the species structure of the sown areas of croplands. The volume of biomass losses was estimated as a result of fires of different severities. It was estimated that during in 2022, landscape fires burned 749.5 thousand hectares thereof: croplands – 419.1 thousand hectares; other natural vegetation – 273.8 thousand hectares; conifer forests – 31.1 thousand hectares; other forests – 25.5 thousand hectares. The impact of the war on landscape fires is confirmed by the large proportion of fires in the 60-kilometre buffer zone along the frontline – 68.9% of the total area of fire. Among all fires, 42.5% of fires occurred in the occupied territory. Total CO₂ emissions from all types of landscape fires reached 5.20 million tons and other greenhouse gases – 0.28 million tons. It is the first detailed mapping of landscape fires with an analysis of each polygon for the whole territory of Ukraine. The results provide important information for assessing the loss of ecosystem services and estimating carbon dioxide emissions as well as for confirming the impact of hostilities on landscape fires

Keywords: wildfires; burned area; CO₂ emissions; land cover type; biomass; mapping

Introduction

An unprovoked Russian full-scale military invasion that started on February 24, 2022, resulted in unprecedented consequences for people, infrastructure, and environment. In particular, disturbances related to battles, shelling, military vehicles and infantry activities, and fortification facility establishment occurred on areas of millions of hectares, including protected areas. Landscape fires, i.e., forest fires, intentional but uncontrollable burning of vegetation residues on cultivated lands (croplands, pastures), uncultivated grasslands or degraded lands, and associated greenhouse gas emissions, became one of the most essential and wide-scale consequences of the war.

Carbon emission assessment of wildfires is an important part of the development of a new green climate global policy and action

plan similar to Green Deal or others. L. Volkova *et al.* (2022) found that a loss of just 1% biomass could be detected between low- and high-severity fires with foliage and partial bark combustion and unburned stem wood. Carbon emissions from forest fires in 2020 across the western United States were in a range from 18.60±1.04 Mg C·ha⁻¹ to 29.70±1.66 Mg C·ha⁻¹ (Bartowitz *et al.*, 2022). According to S. Germand *et al.* (2021) average tree C losses were 114.0 Mg C ha⁻¹ (std. dev. ±9.9 Mg C ha⁻¹) in wet riparian sites and 86.9 Mg C ha⁻¹ (std. dev. ±13.5 Mg C ha⁻¹) in the dry valley site of the southern Canadian montane valley ecosystem, in Waterton Lakes National Park, Alberta Canada.

As a result of high-intensity fires, high tree mortality converts live trees to deadwood, which gradually decomposes. J.E. Stenzel *et*

al. (2019) found that high-intensity fire combusts less than 5% of live tree biomass in mature stands. The regional emissions estimates using widely implemented combustion coefficients are 59%-83% higher than emissions based on field observations.

Despite a significant number of publications on carbon emissions after fires (Zheng *et al.*, 2021), this issue has been researched fragmentarily in Ukraine. Assessment of carbon losses using remote sensing methods in Ukraine was implemented for the Chernobyl Exclusion Zone (CEZ) (Matsala *et al.*, 2023). In this publication, post-fire carbon stock on training forest polygons was calculated by applying local combustion factors within the CEZ. The relative carbon loss was derived using the stand-alone delta of backscatter at vertical-horizontal polarisation or based on the model calibrated with four SAR-based predictors. The total loss of carbon stock resulting from the 2020 catastrophic wildfire was estimated at 156.3 Gg C. Carbon loss in Scots pine stands was 7.4 ± 2.8 Mg C·ha⁻¹. The estimated average carbon loss based on inventory data is $9.3 \pm 5.1\%$ and the mean predicted carbon loss was $11.0 \pm 4.1\%$. According to L.A. Pysarenko & M.V. Savanets (2020), the average long-term values of carbon emissions for the territory of Ukraine vary within the limits of 0.2-1.0 g·m⁻²·month⁻¹. For dry particle flows, the average values are mainly 1.0-3.0 g·m⁻²·month⁻¹. According to the 2023 National Inventory Report (NIR) (2023), the CO₂ emissions from forest fires were 5.75 kt in 2021.

There have been only a few studies to estimate carbon emissions from fires during the war in Ukraine, mainly due to data gaps in such assessment. Among them the most completed assessment of the joint team of L. de Klerk *et al.* (2023), who provided the first and second interim assessments. One of the good reviews of the problem of estimating carbon emissions from fires was made by S. Malo (2023). The main

methodological issues of carbon emissions estimation are assessing the burn area, determining the type of affected vegetation, estimating the total biomass, and calculating the proportion of biomass burned. The main research objective of this study is to estimate carbon emissions from landscape fires in Ukraine in 2022.

Materials and Methods

The carbon emissions in 2022 were calculated throughout the entire territory of Ukraine. The research was conducted following the Convention on Biological Diversity (1992) and the Convention on the Trade in Endangered Species of Wild Fauna and Flora (1973). To achieve the aim of the study, it was necessary to calculate the following indicators: burned areas and fire severity; carbon emission from forest fires; carbon emission from cropland burning; and carbon emissions from fires within other natural landscapes.

Burned areas and fire severity

Two remote sensing data sources were harnessed for fire detection and burn area delimitation. The special wildfire monitoring service OroraTech was used to detect ignition locations. The system uses aggregated data from over 20 satellites for tracking daily fire. It combines different fire detection approaches provided by more than 20 satellites for the daily identification of fire locations. A time series of Sentinel 2 (Level 2A) surface reflectance data was used for mapping the fire perimeter based on the identified ignition points and corresponding dates. Scene Classification (SCL) band classes were applied to exclude clouds, cloud shadows, and snow. Median image mosaics, generated within a 14-day timeframe, were utilized to manually outline fire perimeters. The Copernicus Dynamic Land Cover 100 m resolution map (2019) was used for land cover type identification within the established fire polygons (Buchhorn *et al.*, 2020). The delta NBR (dNBR,

Normalised Burn Ratio) approach was applied to assess burn severity (Key & Benson, 2006). Pre-fire image mosaics were created by selecting the pixels with the highest NBR values in the 40-day window before the fire. Then, post-fire median mosaics were created from cloud-free images within 5, 10, 15, ..., and 40-day intervals after the fire. The burn severity was mapped using maximum dNBR-value composites obtained for the specified post-fire intervals. This iterative method mitigated the impact of potential vegetation regrowth during the post-fire period and ensured sufficient cloud-free data coverage. The dNBR values were categorized into three discrete burn severity classes: low (0.090-0.179), medium (0.180-0.549), and high (more than 0.550) (Myroniuk *et al.*, 2022). Mean values of burn severity levels were calculated for different land cover types (coniferous forests, broadleaf forests, croplands, other natural vegetation, and urban territories), which were subsequently used in carbon loss assessments. The study primarily focused on the emission of carbon compounds such as CO₂, CO, and CH₄, which constitute 95% of wildfire emissions (Urbanski, 2014).

Carbon emission from forest fires

Species and age structure of forest stands were used for carbon emissions estimation. The age and species structure of forest stands determine the total volume of biomass and the level of biomass losses from fires of different inten-

sity. According to the latest data of the forest assessment in Ukraine (Handbook of the Forest Fund of Ukraine, 2012), the distribution of forested area between coniferous and broadleaved species was estimated for each administrative oblast (region) of Ukraine. Then, their areas were distributed between young, middle-aged and premature, mature and overmature forest stands. Further, the total volume of biomass within the classified forest stands was estimated using mathematical models, compiled by A.Z. Shvidenko *et al.* (2014) and A.M. Bilous (2018). The models were selected considering the dominant tree species within a specific region: coniferous (pine, spruce), broadleaf (oak, beech, birch, aspen, and alder). Different types of forest fires as a surface, canopy (crown) or combined can form different degrees of damage: low (damage to the upper layer of the litter, ground cover, undergrowth and slight burning of the bark of tree stems), medium (damage to the bark of tree stems and lower branches of the crown, destruction of trees of category IV and V according to the Kraft scale) and high (destruction of a significant number of elements of the forest stand). There is lack of scientific publications on forest biomass losses due to different intensities of forest fires in Ukraine. Thus, the study used only limited scientific data (Bartowitz *et al.*, 2022; Matsala *et al.*, 2023) and experts' estimates. Coefficients of forest biomass losses due to forest fires are presented in Table 1.

Table 1. Average forest biomass losses coefficients due to forest fires, %

Age group	Fire severity level, dNBR	Component of forest biomass				
		Stem**	Bark	Branches	Undergrowth*	Litter
<i>Coniferous species</i>						
Young (0-20 years)	Low	10	x	10	30	30
	Medium	20	x	30	50	50
	High	40	x	60	100	100
Young (21-40 years)	Low	x	x	10	30	30
	Medium	x	1	20	50	50
	High	x	2	40	95	95

Table 1, Continued

Age group	Fire severity level, dNBR	Component of forest biomass				
		Stem**	Bark	Branches	Undergrowth*	Litter
Middle-aged and premature (41-80 years)	Low	x	x	x	30	30
	Medium	x	1	x	50	50
	High	x	2	5	90	90
Mature and overmature (81 years and older)	Low	x	x	x	30	30
	Medium	x	x	x	50	50
	High	x	1	5	90	90
<i>Deciduous species</i>						
Young (0-20 years)	Low	5	x	10	20	20
	Medium	10	x	20	30	30
	High	30	x	40	80	70
Young (21-40 years)	Low	x	x	x	20	20
	Medium	x	1	10	30	30
	High	x	x	30	70	70
Middle-aged and premature (41-100 years)	Low	x	x	x	20	20
	Medium	x	x	x	25	30
	High	x	1	x	65	70
Mature and overmature (101 years and older)	Low	x	x	x	15	20
	Medium	x	x	x	25	30
	High	x	x	x	65	70

Note: * Undergrowth (living ground cover, young trees, and brushwood); ** – Stem with bark

Source: K.J. Bartowitz *et al.* (2022), M. Matsala *et al.* (2023)

The carbon emissions as a result of forest fires were calculated using the following equation:

$$C_{em} = M_{fr} \cdot K_{cf} \cdot K_{lf}, \quad (1)$$

where C_{em} – volume of carbon emissions, t; M_{fr} – dry matter mass of individual components of biomass, t; K_{cf} – coefficient of carbon content in a component of biomass (bark, branches – 0.5; leaves, living ground cover, litter – 0.45); K_{lf} – coefficient of forest biomass losses due to forest fires of different severity (Table 1).

Carbon emission from fires on cropland

Dominant crop species within the sown areas were determined using the crop area distribu-

tion in different regions of Ukraine. According to the Ministry of Agrarian Policy and Food of Ukraine, in 2022, wheat, barley, sunflower, and corn dominated among crops, covering almost 85% of the sown areas. The following ratios of the mentioned crops were used: wheat – 37.3%, barley – 10.8%, sunflower – 26.1%, and corn – 25.8%. Yields of the crops (in t·ha⁻¹) within each region was determined based on national statistics data (Verner, 2021). Biomass volume was determined by the coefficients of the total yield of surface and root crop residues (Table 2) with the yields of crop species considered (Kokhana & Glushchenko, 2015).

Table 2. Coefficients of yield residues depending on crop harvests

Crops	Coefficient of the total yield of by-products, stubble, and root residues	Non-marketable biomass remaining on field, %	
		by-products	stubble and root residues
Wheat	1.5	53	47
Barley	1.3	52	48

Table 2, Continued

Crops	Coefficient of the total yield of by-products, stubble, and root residues	Non-marketable biomass remaining on field, %	
		by-products	stubble and root residues
Sunflower	3.5	50	50
Corn	1.4	58	42

Source: A.V. Kokhana & L.D. Glushchenko (2015)

The calculations considered that not only by-products but also the main crop would be lost due to fire in the 60-km buffer zone during May and July 2022, as a high density of shelling was observed. Volumes of carbon emissions as a result of fire on croplands were calculated by the following equation:

$$C_{em} = B_{pl} \cdot K_{cf} \cdot K_{pf}, \quad (2)$$

where C_{em} – volume of carbon emissions, t; B_{pl} – plant biomass in a completely dry state, t; K_{cf} – coefficient of carbon content in a unit of biomass (0.45); K_{pf} – coefficient that considers the fire severity (low – 0.9; medium and high – 1.0). *Carbon emission from fires on other natural landscapes*

Using the Official website of the State Statistics Service of Ukraine (n.d.) for geodesy,

cartography, and cadastre, the regional structure of other landscape types was determined. In 2020, the regional structure of landscapes, in addition to forest areas and arable land, also includes hayfields, fallows, and pastures. According to the Land Directory of Ukraine (2020), the share of each of the listed types of agricultural landscapes within each region was calculated. Productivity and biomass volumes were determined by types of landscapes. The productivity of the mentioned types of landscapes (in t·ha⁻¹) within each region is estimated following scientific data from numerous botanical and ecological publications and grouped by natural zones of Ukraine (Table. 3). Biomass losses are differentiated depending on the level of site damage and the type of landscape. Equation 2 was used to estimate carbon emissions from fires within other natural landscapes.

Table 3. Productivity of certain types of landscapes within natural zones

Natural zone	Dry matter yield, t·ha ⁻¹		
	Hayfields	Pastures	Fallows
Steppe	2.7	2.4	1.8
Forest steppe	4.2	3.8	2.8
Ukrainian Polissya	3.8	3.4	2.5
Ukrainian Carpathians	3.2	2.8	2.1

Source: M.I. Stakal (2020), V.I. Grigoriev et al. (2021)

As a result of applying the described algorithm by category (forest fires, fires on cropland, fires on other natural landscapes) burned areas by burn severity classes, biomass and carbon losses and greenhouse gas emissions were determined.

Results and Discussion

The total area of landscape fires in Ukraine in 2022 reached 749.5 thousand hectares. The majority of the affected territories were agricultural lands (croplands), accounting for 419.1 thousand hectares, and other natural vegetation

(abandoned lands) amounting to 273.7 thousand hectares. Forest fires burned 56.7 thousand hectares. In total, about 20 thousand fires were detected in 2022. A significant proportion of these fires occurred within a 60-kilometer buffer zone along the frontline, comprising 69% of the total fire-affected area, and 43% of all fires occurred in occupied territories (Zibtsev *et al.*, 2023). The territories most affected by fires are those where

active military operations were ongoing in the eastern, southern, and northern parts of Ukraine. Specifically, the most significantly impacted regions were Donetsk (146.3 thousand hectares), Kherson (84.1 thousand hectares), Kyiv (70.9 thousand hectares), Zaporizhia (65.6 thousand hectares), Luhansk (65.6 thousand hectares), Mykolaiv (47.7 thousand hectares), and Kharkiv (42.6 thousand hectares) (Fig. 1).

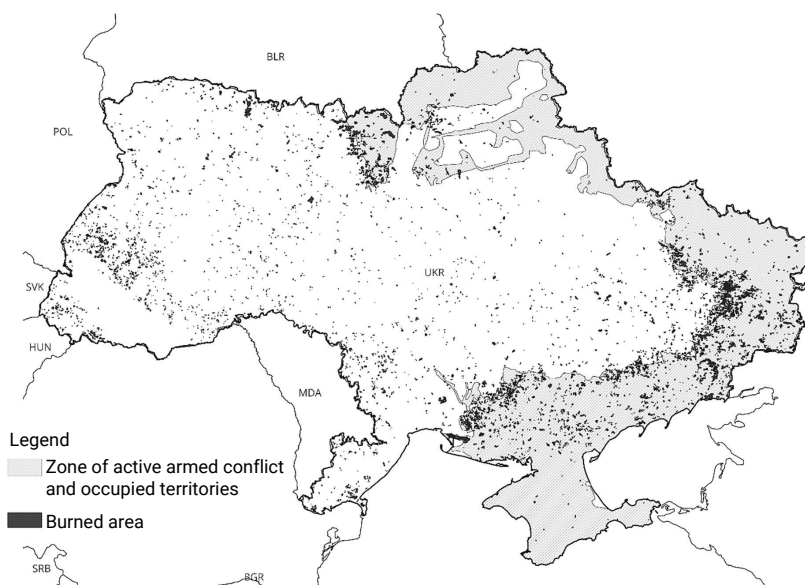


Figure 1. Distribution of fire perimeters in 2022 over the territory of Ukraine

Source: S. Zibtsev *et al.* (2023)

The distribution of the area affected by fires of different severity levels (based on dNBR values) showed that natural landscapes were mostly affected by medium burn severity (43.6-47.7%

of total area). High fire severity ($dNBR \geq 0.550$) observed on a small proportion of forested areas and, among all other land categories, high fire severity prevailed on croplands (Table 4).

Table 4. Assessing the condition of woody plants

Land category	Proportion of fire severity classes, %		
	Low	Medium	High
Coniferous forest	51.9	43.6	4.5
Other forest	46.8	44.4	8.8
Other natural vegetation	34.0	47.7	18.3
Cropland	22.7	45.9	31.4
Total	29.1	46.3	24.6

Source: calculated by the authors

Emissions of carbon dioxide from landscape fires in Ukraine reached 5.20 million tons in 2022 (Table 5). Carbon emissions were largest from fires on croplands (59%) and on uncultivated land (24%). Forest fires emitted over 16.9% of total carbon emissions (12.6% from fires in pine forests and 4.3% in broadleaf and mixed forests). Average carbon losses per 1 hectare during fires in coniferous forests were more than 2 times higher compared to other landscape types and broadleaf forests. Such

high carbon losses are associated with significant fuel load in pine forests and higher fire intensity. In broadleaf prevailing fires of low intensity burning dry surface fuel.

Results of the assessment done by L. de Klerk *et al.* (2023) showed a significantly different distribution of areas of fires by land cover types in comparison with current results (Table 6): 11.3% less area of fires on agricultural lands and 78.6% less area of fires in other landscapes (abandoned lands).

Table 5. Burned area, biomass and carbon losses, CO₂ emission by land category

Land category	Burned area, thous. ha	Biomass loss, Mt	Biomass loss, t·ha ⁻¹	Carbon loss, Mt	Carbon loss, t·ha ⁻¹	CO ₂ emission, Mt	Other greenhouse gases, Mt
Coniferous forest	31.1	0.33	10.66	0.14	4.59	0.53	0.05
Other forest	25.5	0.17	6.49	0.07	2.69	0.25	0.02
Other natural vegetation	273.8	0.78	2.83	0.35	1.28	1.28	0.06
Cropland	419.1	1.90	4.54	0.86	2.05	3.14	0.15
Total	749.5	3.18	4.33	1.42	1.89	5.20	0.28

Source: calculated by the authors

Table 6. Comparison of areas of fire on land categories in L. de Klerk *et al.* (2023) report and current study

Land category	Area of landscape fires, thous. ha (de Klerk <i>et al.</i> , 2023)	Area of landscape fires, thous. ha (current study)	Difference	
			Hectare	%
Forests	58.9	56.7	2215	3.9
Agricultural lands	371.7	419.1	-47409	-11.3
Other landscapes	58.6	273.7	-215167	-78.6

Source: prepared by the authors based on L. de Klerk *et al.* (2023)

Even though in our assessment the area of fires on croplands and grasslands was more than 262.6 thousand ha, the calculated carbon emissions from such types of lands in the study of L. de Klerk *et al.* (2023) were 11.69 million tons higher (Table 7). The reason for such difference is a peculiarity of the methodology for calculating biomass burned during fires for different types of natural and cultural landscapes. The

release of carbon during forest fires according to L. Klerk *et al.* (2023) is 210.8 t·ha⁻¹, while in our study this indicator is on average 13.7 t·ha⁻¹ (15 times lower). Among all landscape fires in 2022 in Ukraine, only a small share are forest crown fires that result in immediate biomass burning and carbon release. Fire weather during the fire season of 2022 was rather safe in the northeastern and eastern regions of Ukraine

and close to pretty safe in the 2013 year. More complete burning of biomass was typical for open types of landscapes (agricultural lands and other landscapes). Another source of differences with the report of L. de Klerk *et al.* (2023) is

methodological approaches in assessing the productivity of biomass on agricultural lands and other landscapes, which also contributed to an overestimation of 49.6-50.3% for CO₂ emissions in the L. de Klerk *et al.* (2023) report (Table 7).

Table 7. CO₂ emissions in the different land categories

Land category	CO ₂ , Mt (current study)	CO ₂ , Mt (de Klerk <i>et al.</i> , 2023)	CO ₂ , t·ha ⁻¹ (current study)	CO ₂ , t·ha ⁻¹ (de Klerk <i>et al.</i> , 2023)
Forests	0.78	12.41	13.7	210.8
Cultivated lands	**3.14	*4.19	7.5	11.3
Other landscapes	1.28	0.41	4.7	7.0
Total	5.20	17.01	-	-

Note: *all agricultural lands included croplands, pastures, and haymakers; **croplands

Source: developed by the authors based on L. de Klerk *et al.* (2023)

L. de Klerk *et al.* (2023) used data on fires (number of fires, fire start and end time, coordinates of the boundaries of each fire, land categories for each fire) from fire prevention information systems: Fire Information for Resource Management System (FIRMS) (n.d.) and the European Forest Fire Information System (EFFIS) (n.d.). Following the data given by L. de Klerk *et al.* (2023), 75% of forest fires in 2022 occurred in coniferous forests, 21% in broadleaf forests, and 4% in mixed forests. It is assumed that 75% of fires are canopy (crown), 25% – surface.

According to current research data, 55% (31.1 thousand hectares) of forest fires occurred in coniferous forests, mostly pine stands while 45% (25.5 thousand hectares) – in broadleaf and mixed forests. Analysis of the dNBR index showed that 30% of the fire areas are of low severity – weak or average surface fires. At this level, only the upper layer of the forest litter, the living above-ground forest grasses and, partially, undergrowth burns out. The bark of trees can be burned up to 1 meter in height with some temperature impact on external live layers of stems. More heavy impact on stands occurred with intensive ground fires (up to 1.5 flame length) that were a case in 46% of areas of fires, while severe impact (crown fires) occurred

in 24% of all fires. In the L. de Klerk *et al.* report (2023), it is assumed that 70% of forest biomass is lost due to the impact of crown fires that resulted in carbon emissions in the year of fires according to the Tier 1 approach of the Intergovernmental Panel on Climate Change (IPCC) guidelines. The average stock of wood was taken at the level of 233 m³·ha⁻¹. The same approach was used when estimating emissions from forest fires in the 2023 National Inventory Report (NIR) (2023).

L. de Klerk *et al.* (2023) considered emissions of other greenhouse gases: carbon monoxide (CO), methane (CH₄), non-methane volatile organic compounds (NMVOC) and nitrogen compounds (N₂O, NO_x). According to S. Urbanski (2014), emission factors are 1600-1641 (wildfire), 1705 (grassland) g/kg CO₂; 95-135 (wildfire), 61 (grassland) CO; 3.38-7.38, 1.95 (grassland) CH₄; 23.15-33.87 (wildfire), 16.87 (grassland) NMOC; 1.0-2.0 (wildfire), 2.18 (grassland) NO_x, the share of others is insignificant. According to H. Keith *et al.* (2014) in temperate Australian forests, 6-7% of biomass is lost as a result of low-severity wildfires and 9-14% as the result of high-severity wildfires. Direct emissions occurring during forest fires are caused by the burning of such forest

combustible materials as leaves, branches, woody debris, and other organic material on the soil surface. The proportion of the total carbon stock burned was relatively small (more than half of the stock losses from burning came from short-lived biomass components). A significant proportion of biomass, although not burned, is redistributed to dead components. The decomposition of these components and new recovery have the largest impact on carbon stocks in the coming decades. M.D. Hurteau & M.L. Brooks (2011) noted that long-term effects of fire are manifested in indirect fire emissions from the long-term decomposition of trees that have dried up, but not consumed by fire; this source can be as much as three times the size of direct carbon emissions. Established carbon dioxide emissions for forests during fires were 13 times lower compared to the data of L. de Klerk *et al.* (2023). Such differences were caused by significant differences in calculation methods: this article considered carbon emissions directly during a fire without addressing long-term changes in the redistribution of carbon in fire-damaged forests caused by post-fire tree mortality.

Conclusions

Russian military aggression against Ukraine has caused a drastic increase in the number and area of forest fires in Ukraine. Besides disturbing forests and open natural landscapes, biodiversity and negative social impacts, wildfires also produce large amounts of carbon emissions. Based on the data on wildfires mapped by the authors using remote sensing data of Sentinel 2 satellite images, this paper presents the results of the assessment of carbon emissions from landscape fires that occurred in Ukraine in 2022. The war was found to be a major factor in the fire situation, with 69% of the total area affected by fires in the 60-kilometre buffer zone along the frontline. In general, in 2022, there were about 20 thousand landscape fires on a

total area of 749.5 thousand hectares, with the most affected agricultural land (arable land) – 56%, other natural vegetation (abandoned land) – 37%, and forest fires – 7%.

It was estimated that direct emissions of carbon dioxide due to landscape fires in 2022 amounted to 0.78 million tons (775348.8 tons) on forest lands, on croplands – 3.14 million tons (3142750.8 tons), other landscapes 1.28 million tons (1280089.4 tons). Compared to de Klerk *et al.* (2023), the area of forest fires in our study was smaller by 3.9%, while fires on agricultural lands were higher by 11.3%, and other landscape fires by 78.6%.

To obtain more accurate data on carbon emissions from fires in Ukraine's natural landscapes and to assess the negative environmental consequences caused by the war, it is necessary to conduct massive fieldwork to establish burning intensity (burn severity) for different types of landscapes. The next step to improve the proposed methodology for estimating carbon emissions after a fire is to predict the post-fire dynamics of forest ecosystems, which may include the recovery or degradation of damaged territories. The results also are an important step toward collecting scientifically proven evidence of the ecocide of the Russian war against Ukraine of the war in international courts.

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Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Оцінка викидів вуглецю від ландшафтних пожеж в Україні за період війни у 2022 році

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Анотація. Військова агресія російської федерації та пов'язані з нею соціально-економічні та екологічні наслідки суттєво вплинули на клімат та виробництво екосистемних послуг через пошкодження лісів, екосистем, ландшафтні пожежі та викиди газів в атмосферу. Метою дослідження було оцінити викиди вуглецю внаслідок ландшафтних пожеж в Україні упродовж 2022 року. Для виявлення пожеж використовувалася технологія моніторингу лісових пожеж OroraTech, а периметри пройдених вогнем ділянок окреслювалися за допомогою часових

рядів супутникових знімків Sentinel 2. Для розподілу пройдених пожежами площ за типами земного покриву використовувалася карта Copernicus Dynamic Land Cover. Викиди вуглецю були розраховані за даними інтенсивності пожеж (dNBR) та частки спаленої біомаси в різних типах земного покриву. Моделі біомаси були обрані з урахуванням домінуючих деревних порід у конкретному регіоні та домінуючої видової структури посівних площ сільськогосподарських культур. Обсяги втрат біомаси оцінювалися з врахуванням інтенсивності пожеж. Підраховано, що протягом 2022 року площа ландшафтних пожеж сягнула 749,5 тис. га, з них 419,1 тис. га на орних землях; 273,8 тис. га в інших природних типах рослинності; 31,1 тис. га в хвойних лісах; 25,5 тис. га в інших лісах. Вплив війни на ландшафтні пожежі підтверджується великою часткою пожеж у 60-кілометровій буферній зоні вздовж лінії фронту – 68,9 % від загальної площі пожеж. Серед усіх пожеж 42,5 % пожеж сталися на окупованій території. Сумарні викиди CO₂ від усіх видів ландшафтних пожеж сягнули 5,20 млн тонн, а інших парникових газів – 0,28 млн тонн. Це перше детальне картографування ландшафтних пожеж з аналізом кожного полігону для всієї території України. Результати дослідження надають важливу інформацію для оцінки втрат екосистемних послуг та оцінки викидів вуглецю, а також для підтвердження впливу бойових дій на ландшафтні пожежі

Ключові слова: лісові пожежі; вигоріла площа; викиди CO₂; тип ґрунтового покриву; біомаса; картографування

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