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Introduction and breeding of purple-leaved hazel in the Forest-Steppe of Ukraine

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Abstract. This study was conducted in 2023-2024 to clarify the origin and introduction of purple-leaved hazel, and to examine the morphological and physiological characteristics of the best genotypes developed by the authors. Morphometric analysis of nuts, quantitative and qualitative

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composition of pigments in leaves in dynamics, and observation of the influence of abiotic and biotic environmental factors were carried out. It was found that there were mutants in *Corylus* with red/purple colouration of the pellicle of kernels and/or leaves. They have been found repeatedly in different places in Europe, belonging to the species *Corylus avellana* and/or *Corylus maxima*. Taxonomists consider these taxa to be distinct; however, molecular studies suggest that *Corylus maxima* should be synonymised with *Corylus avellana*. The best selections of purple-leaved hazel are characterised by high-quality nuts weighing 2.5-3.2 g with a kernel percentage of 48.0-51.7. The content of chlorophyll a, chlorophyll b, carotenoids, and anthocyanins in purple-leaved selections 'Profesorskyi', 'Aspirantskyi', and 'Akademichnyi' was generally higher than in green-leaved varieties, although this difference was not statistically significant in most cases, except for anthocyanins. The high anthocyanin content in the leaves (up to 0.69 mg/g in May) and in the fruit involucres gave these genotypes exceptional decorative effect during the first half of the growing season and beyond. These genotypes had high winter hardiness and drought resistance and are well adapted to local soil and climatic conditions. Among the biotic environmental factors, the nut weevil *Curculio nucum* (damaging the nuts), and the powdery fungus *Phyllactinia guttata* (affecting the leaves) had a negative impact. The fungus *Erysiphe corylacearum*, new to Ukraine, was also found on the leaves. These findings support the wider introduction of purple-leaved hazel, as the best genotypes are highly ornamental and also produce nut. The obtained data will be useful for forest restoration, landscaping and amateur gardening

Keywords: *Corylus avellana*; ornamental plants; anthocyanins; nut weigh; kernel percentage; powdery mildew

Introduction

Studying the introduction and breeding of purple-leaved hazel is essential for several practical and scientific reasons. This plant, *Corylus avellana*, is a valuable ornamental species used in landscaping and horticulture. Its unique purple or reddish leaves attract gardeners and landscape architects, leading a significant demand for its cultivation and propagation. Understanding how to introduce new varieties of purple-leaved hazel into different climatic conditions and soil types is crucial for their successful integration into various environments. Additionally, breeding purple-leaved hazel aims to enhance characteristics such as disease resistance, cold hardiness, and productivity. The development of new varieties can improve both the decorative and commercial qualities of the plant, which is important for gardening and agriculture. Furthermore, this research contributes to biodiversity conservation and the advancement of breeding technologies, potentially benefiting forestry and green construction. Overall, studying the introduction and breeding of purple-leaved hazel not only improves its cultivation but also plays a vital role in preserving the ecological balance (Hicks, 2022).

Recent studies have extensively examined anthocyanin pigmentation in various woody plant species, including *Corylus*, emphasising its protective role against abiotic stressors. K.D. Gu *et al*. (2019) explored how anthocyanins contribute to environmental resilience in horticultural crops, particularly in terms of UV protection and oxidative stress resistance. However, while these studies provide a general understanding of anthocyanin functions, they lack specific insights into the performance of purple-leaved hazel under different ecological conditions.

V.M. Mezhenskyj *et al.* (2024) analysed the value of plants with anthocyanin-rich organs and their importance for landscape architecture, fruit cultivation, and nurseries, as well as their nutraceutical value. O. Johnson & R. Moore (2023) focused on breeding advancements in *Corylus avellana*, detailing the development of new cultivars with unique growth forms such as compact, weeping, and contorted varieties. Their study underscored the increasing ornamental value of purple-leaved hazel but did not assess its agronomic performance or physiological traits under local climatic conditions in Ukraine. K. Król & M. Gantner (2020) investigated the economic significance and commercial potential of *Corylus avellana*, emphasising its role in global nut production. Their study examined hazelnut cultivation trends, market demand, and profitability, highlighting the increasing consumer interest in hazelnuts for their nutritional value and industrial applications. However, while their research provided a broad economic perspective, it did not focus on specific morphological or physiological traits of different hazelnut cultivars, particularly purple-leaved genotypes.

Researchers D. Shataer *et al.* (2021) analysed the chemical composition of *Corylus avellana* kernels and evaluated their biological properties, including anti-inflammatory, antimicrobial, and antioxidant activities. Their findings demonstrated the significant health benefits of hazelnuts due to their rich polyphenolic content and bioactive compounds. The study primarily addressed kernel composition without considering the potential effects of leaf pigmentation on the plant's biochemical and physiological processes. Additionally, no differentiation was made between green- and purple-leaved hazelnut selections.

A. Allegrini *et al.* (2022) explored *Corylus avellana* as a multipurpose species within the framework of the circular economy, emphasising its role in sustainable agriculture, agroforestry, and landscape management. Their research highlighted the diverse applications of hazelnut cultivation beyond nut production, including its potential for erosion control, carbon sequestration, and biodiversity enhancement. However, the study did not address the ornamental value of purple-leaved hazelnuts or their adaptation to different environmental conditions, leaving a gap in understanding their role in ecological and urban green spaces in Ukraine. Meanwhile, purple-leaved hazel varieties have been included in Ukraine's State Register of Varieties Suitable for Distribution (Ministry..., 2024), but research evaluating their adaptation to the country's environmental conditions remains insufficient.

The purpose of this study was to evaluate the best selections of purple-leaved hazel of their own breeding in terms of morphological characteristics and physiological properties for their introduction as ornamental and nut plants for agroforestry, landscaping architecture and amateur growing.

Materials and Methods

Plant Materials. The seedlings of 'Akademik Yablokov' and 'Moskovskij Rubin' were planted in the orchard of the Educational, Research and Production Laboratory "Genetic Resources, Introduction and Breeding of Rare Fruits and Ornamental Plants" of prof. V.L. Symyrenko Department of Horticulture. This orchard is located at the Agronomic Research Station of the National University of Life and Environmental Sciences of Ukraine (NULESU) in Pshenychne village, Bila Tserkva district, Kyiv region which is part of the forest-steppe natural zone. The purpose of establishing and maintaining trees and shrubs in NULESU was to preserve the gene pool and breeding work with fruit and ornamental plants. The collection also had an educational value. Three best selections of *Corylus avellana* named 'Profesorskyi', 'Aspirantskyi', and 'Akademichnyi' were used. The adult multi-stemmed shrubs were grown at a planting distance of 5 × 4 m. Standard cultural practices were applied, except irrigation. To compare the pigment content of purple-leaved and green-leaved hazel, leaves of the green-leaved cultivars 'Mortarella', 'Tonda Gentile delle Langhe', and 'Yamhill' were used. The study was conducted in accordance with the ethical standards of the Convention on Biological Diversity (June 1992), which ensures the conservation and sustainable use of biological diversity.

Morphometric analyses. A sample of 20 nuts per genotype collected in 2023-2024 was randomly used for nut traits. In the prof. V.L. Symyrenko Department of Horticulture laboratory, nut samples were dried to constant mass prior to analyses and measurements. Only two linear dimensions of the nut, length and diameter, were measured using a mechanical calliper. It was because these nuts had virtually no difference in nut thickness and nut diameter, and the shell thickness was assessed after manual cracking of the nuts. All measurements were taken in mm. For each sample, the nut and kernel weight (in grams) were measured using an Adventurer™ (Ohaus, China, 2010) electronic laboratory balance. The percentage of kernel was calculated by the following equation: kernel weight / nut weight. Nut shape index was calculated by the following equation: nut length (mm) / nut diameter (mm).

Determination of pigments. Biochemical analyses of hazel leaves were carried out in the Laboratory of Breeding and Technology of Growing Small Fruit Crops of the Institute of Horticulture of the National Academy of Sciences and in independent laboratories for assessing the quality of fruits. The pigments content was determined by the spectrophotometric method using ULAB 102UV (China) spectrophotometer, according to the relevant methods (Kryventsov, 1982; Lichtenthaler, 1987; Hrynenko & Zhuravel, 2017). The data was expressed as mg/g of fresh weight. To determine the pigments, the second and third fully expanded leaves of the shoots of the current year were used.

Impact of environmental factors. Winter hardiness and drought tolerance were assessed in the field by observing plant condition. Pests and pathogens that damage and infect leaves and fruit were identified.

Statistical analysis. The acclimatisation score was calculated using the appropriate formula (Kokhno & Kurdyuk, 1994). Analysis of variance (ANOVA) was performed using Microsoft Excel software (Microsoft Corporation, Roselle, IL, USA). Fisher's least significant difference (LSD) test was used to determine significant differences between means at a 95% confidence level ($P \leq 0.05$). Results are presented as the mean ± standard deviation.

Results and Discussion

Ecological, economic, and ornamental significance of Corylus avellana L. *Corylus avellana* L. (*Betulaceae*) is a component of nemoralis vegetation, which began to form in the Mesozoic era. During the post-glacial period of the early Holocene, it grew only in the western part of the modern territory of Ukraine, subsequently migrating eastward. In pine stands, hazel had only pine and sometimes birch as competitors. Here it formed dense thickets and replaced forests with hazel groves. In contrast, there was little hazel in spruce forests. In the Middle Holocene, hazel occupied most of the territory of Ukraine, except for the steppe regions (Nejshtadt, 1957). At present, according to V.P. Tkach *et al*. (2024) *Corylus avellana* is included in the undergrowth of oak-birch and oak-hornbeam forests. H.P. Ishchuk (2007) points out that it is dominant in the undergrowth of forest cultures of *Juglans nigra* L. According to V.Ye. Sliusarchuk (2006) *Corylus avellana* performs protective functions in steppe forestry, in phytomelioration plantations it protects soil from water erosion, improves hydrological regime, and soil fertility. As a pioneer species it is useful for forest restoration and forest succession.

The hazel is one of the five most important nut crops after cashew, walnut, almond, and chestnut. In Ukraine, the area of hazelnut plantations increased from 100 to 300 hectares (a 66.7% increase), and gross production rose from 20 tons to 210 tons (a 90.5% increase). In the next ten years it is planned to increase the total area of hazelnut plantations to 15 thousand hectares (Mezhenskyj, 2022). Hazelnuts are very nutritious. They are consumed fresh, dry and roasted, used in cooking for various dishes and in the confectionery industry. The oil from the kernels is of nutritional and technical importance and is also used in painting and perfumery. The oil cake is used to make halva and as a substitute for coffee. Young leaves are used in cabbage rolls, soups, and as a tea substitute. Leaves and shoots are fodder for wild and domestic animals (Molnar, 2011).

Hazel wood is thin, white with a reddish tinge, not heavy, soft and easy to split. It is used for hoops, rivets, bent furniture, turnery and carpentry, fencing, wattle and daub, canes and poles; thin branches are used for baskets. The wood burns well and gives off a lot of heat. Charcoal is used to make gunpowder and is good for filtering and drawing. Hazel sawdust clarifies vinegar and clears cloudy wine. The bark can be used as a tanning agent to make the hide yellow. Hazel fruits, bark, leaves, pollen and roots are used in folk medicine. The use of drugs is indicated for dilated veins, periphlebitis, ulcers, capillary hemorrhages. They are used in prostatitis, liver and kidney diseases, anemia, diabetes, hypertension, atherosclerosis, etc. *Corylus avellana* belongs to the taxol-producing angiosperms. Taxol is used to treat breast, ovarian, and non-small cell lung cancer (Goktepe-Atilgan *et al.*, 2023).

The "waste" (leaves, skins, shells, hulls, and pruning material) from hazelnut cultivation is interesting to be valorised as a source of chemical compounds for human health, even more than as a biomass fuel or for biochar applications. *Corylus avellana* can be used for the production of hazelnuts and truffles because its roots form a symbiosis with black and summer truffles.

Hazel is important as an ornamental. Plants with purple leaves are particularly attractive, with anthocyanin colouration dominating in the first half of the growing season. In spring, purple spikes are also attractive. Red pigmentation is also seen in dormant buds, female flowers, husks, and nuts. Many popular ornamental hazelnut cultivars with purple leaves have now been developed in Europe and North America (Johnson & Moore, 2023).

Thus, *Corylus avellana* is a valuable multi-purpose species that plays an important role in forestry, agriculture, industry, and medicine. Its ecological significance in afforestation, erosion control, and phytomelioration, combined with its economic potential in nut production, wood processing, and pharmaceutical applications, highlights its relevance for sustainable resource utilisation. The growing interest in hazel cultivation and the diversification of its applications further emphasise its importance in both ecological restoration and commercial production.

Introduction and breeding of purple-leaved hazel in Ukraine. For a long time cultivated varieties of filbert were attributed to separate species *Corylus maxima* Mill., separating them from the common hazel – *Corylus avellana,* but according to molecular and structural analyses, *Corylus maxima* belongs to the large polymorphic species *Corylus avellana* (Bassil *et al.*, 2013). In *Corylus avellana* populations, red colouration of leaves, buds, female and male flowers occurs. Purple-leaved hazel was introduced to Kyiv in the early 20th century (Dubovyk, 1934). Currently, *Corylus maxima* 'Purpurea' occurs in the botanical gardens and parks of Askania-Nova, Dnipro, Bila Tserkva, Zhytomyr, Ichnia, Kyiv, Lviv, Nikita, Odesa, Uzhhorod, Uman, Kharkiv, Chernivtsi, Kamianets-Podilskyi and *Corylus avellana* 'Atroprpurea/Purpurea' and 'Fuscorubra' – in Bila Tserkva, Kyiv, Lviv, Uman, Kharkiv (Kosenko, 2002).

In 2021, for the first time, the purple-leaved hazelnut variety 'Barbacan BS 1' was registered in the State Register of Varieties of Ukraine. It was selected by Ihor Tsybenko (pers. comm., 2024) in plantations in Poland, with subsequent selection in vegetative progeny. In 1979, Mykola Matvienko (pers. comm., 2024) at the Institute of Horticulture of the NAAS of Ukraine received offspring from the pollination of 'Karamanovskij' × 'Moskovskij Rubin' (Kosenko *et al.*, 2016). From this he selected a number of promising purple-leaved hybrids, which he named 'Bahrianyi', 'Bahriana Bulava', 'Bahriana Bochka', 'Bahriana Kulia' and 'Bahriane Sontse'. In 2022, the cultivar 'Bahrianyi' was included in the State Register of Plant Varieties of Ukraine. In 1991, a collection of hazelnut varieties obtained from the Lozovatskyi Nursery was planted at the Bakhmut Experimental Station of Nurseries Cultivation. The collection included purple-leaved varieties such as 'Akademik Yablokov', 'Moskovskij Rubin', and 'Pushkinskij Krasnyj'. Subsequently, the grafted specimens of 'Akademik Yablokov' and 'Moskovskij Rubin' onto *Corylus colurna* L. were planted in a separate, isolated area for the purpose of harvesting them for hybrid seedlings. In the spring of 2014, the hybrid seedlings were planted in the experimental garden of the National University of Life and Environmental Sciences of Ukraine, located near Kyiv. There is considerable variability among the seedlings, particularly with regard to nut size and nut shape, kernel percentage, time for fruit ripening, and yield. Three best hybrids, selected for a set of economically valuable traits, were designated 'Profesorskyi', 'Aspirantskyi', and 'Akademichnyi'. Today, breeding work with the offspring of these hybrids continues at the Khorol Botanical Garden.

Content of pigments. While most trees and shrubs including *Corylus* species have green leaves, there are purple leaves as well. The popularity of purple-leaved hazel is due to the natural colour of its leaves. For this reason, it has undoubted advantages in ornamental gardening over most plants with green leaves. The purple-leaved hazel is cultivated for its functional and ornamental uses as a street and park plant. The use of purple-leaved hazel allows specialists to solve many problems in landscaping and to create highly decorative and effective compositions of woody plants (Fig. 1).

Figure 1. Purple-leaved and green-leaved hazel plants
Source: authors'photo

The intense anthocyanin colour of the leaves is characteristic of purple-leaved hazel in the first half of the growing season. As time goes by, the anthocyanin intensity decreases and the leaves turn green, at which point the beautiful colour of the nut involucre comes to the fore as a decorative feature (Fig. 2).

Figure 2. Attractive appearance of the purple-leaved hazel husk
Source: authors'photo

In the process of photosynthesis, chlorophylls play a crucial role in light absorption, energy transfer and electron transfer. The main pigment is chlorophyll a. The proportion of chlorophyll b is about one third of the total chlorophyll. The amount of chlorophyll in the plant changes during the vegetative period, gradually increasing until the flowering phase and decreasing from flowering to the end of the vegetative period.

The maximum chlorophyll a content was observed in early July, with values of 2.49 mg/g and 2.39 mg/g recorded in green-leaved and purple-leaved hazel samples, respectively. Subsequently, during the month of July, the chlorophyll a content declined by 1.7 and 1.3 times in green- and purple-leaved hazels, respectively (Fig. 3).

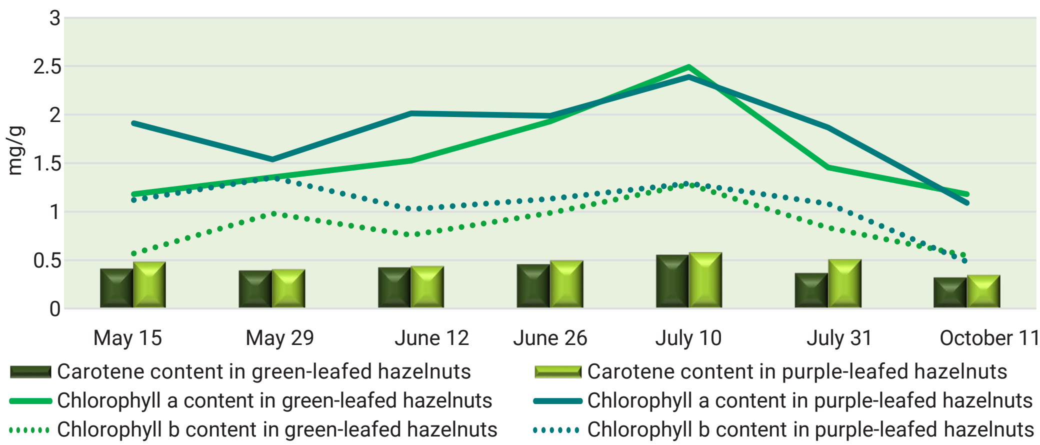


Figure 3. Dynamics of carotene, chlorophyll a, chlorophyll b contents in hazel leaves during the growing season, 2023
Source: compiled by the authors

Throughout the growing season, leaves of red-leaved hazel generally contained more chlorophyll a, except at the end of the growing season. However, this difference was not statistically significant until the first determination in mid-May, when the chlorophyll a content was 1.90 mg/g and 1.44 mg/g for purple- and green-leaved hazel, respectively. Furthermore, a higher chlorophyll b content was observed in the leaves of purple-leaved hazel compared to green-leaved hazel during the growing season. However, these differences did not reach statistical significance. Concurrently, the chlorophyll a/chlorophyll b ratio demonstrated higher levels in green-leaved hazel, though this increase also lacked statistical significance. It should be noted that there is no direct relationship between chlorophyll content and the intensity of photosynthesis, as the latter is determined by the complex interaction of light intensity, its spectral composition, and temperature. The dynamics of carotenoids in hazel leaves is similar to the changes in chlorophyll content, reaching the highest values in early July, 0.55 mg/g and 0.58 mg/g in green- and purple-leaved hazels, respectively. More carotenoids were found in purple-leaved hazel during the growing season, but the difference was not statistically significant.

Anthocyanins, which give tissues their specific colours, are also present in hazel leaves. Anthocyanins are important protective substances that help plants resist stresses such as low temperatures and radiation. Anthocyanins absorb radiation that is poorly absorbed by chlorophyll. The influx of anthocyanins into the leaves is observed in spring and fall, i.e. during cold periods of vegetation. Plants rich in anthocyanins are more resistant to adverse environmental conditions. This is probably due to the fact that anthocyanins activate enzymes of the oxidase class. Together with other plant phenols, flavonoids may be involved in the formation of plant resistance to disease. Anthocyanin plant organs may also have an anti-herbivory function. In addition, both the defensive and physiological functions of anthocyanins may occur simultaneously in plants. It is possible that anthocyanins play a role in plant defence. Anthocyanin pigments absorb UV light as well as visible light and have been proposed to act as UV protectants. J.-H.B. Hatier & K.S. Gould (2008) reviewed three major functional hypotheses for anthocyanins, namely: protection of chloroplasts from the deleterious effects of excess light; attenuation of UV-B radiation; and antioxidant activity, and concluded that none of these hypotheses adequately explains the variation in the spatial and temporal patterns of anthocyanin production because the degree to which each of these processes is affected by anthocyanins varies greatly among plant species. Therefore, anthocyanins may have a more indirect role as modulators of reactive oxygen signalling cascades involved in plant growth and development, responses to stress, and gene expression. In addition, the prevalence of anthocyanin-coloured clones in ornamental horticulture and landscaping is explained by the attention of gardeners, who pay special attention to them for their exceptional decorative value. In a typical hazel, trace amounts of anthocyanins were detected on May 15 (0.01 mg/g), June 12 and July 10 (0.003 mg/g each), and July 31 (0.02 mg/g) (Fig. 4). At this stage, the tips of young shoots with leaves exhibited a slight anthocyanin tint, similar to many other green-leaved species, which fades over time.

In contrast, the leaves of the 'Profesorskyi', 'Aspirantskyi', and 'Akademichnyi' selections (Fig. 4) contained high amounts of anthocyanins, 0.62 mg/g, 0.69 mg/g, and 0.45 mg/6, respectively, on May 15. Their number gradually decreased and was halved by the end of May. A month later, there were three to four times fewer of them (Fig. 5, 6). As a result, the photosynthetic apparatus of the purple hazel is protected more reliably and for a longer period of time from excessive solar radiation.

As the leaves matured, they became greener, with only the apical leaves retaining some pigmentation, although their anthocyanin content was significantly lower than at the beginning of the season. From the end of June until the end of the growing season, they anthocyanin content was low (0.01-0.05 mg/g), but still higher than in the green-leaved cultivars. A certain difference in colour intensity in the studied selections at the beginning of the growing season was later diminished.

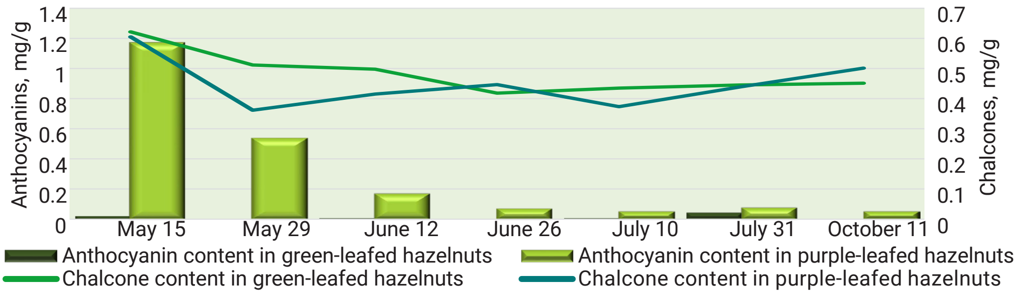
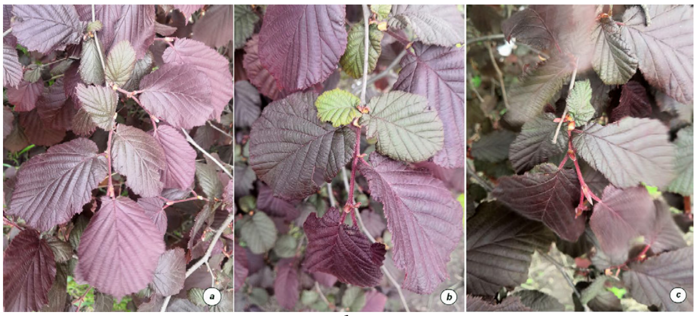


Figure 4. Dynamics of anthocyanin and chalcone contents in hazel leaves during the growing season, 2023

Source: compiled by the authors



a *b* *c*

Figure 5. Leaves of young shoots of purple-leaved hazels, May 15, 2023

Note: a – 'Profesorskyi', b – 'Aspirantskyi', c – 'Akademichnyi'

Source: authors' photo

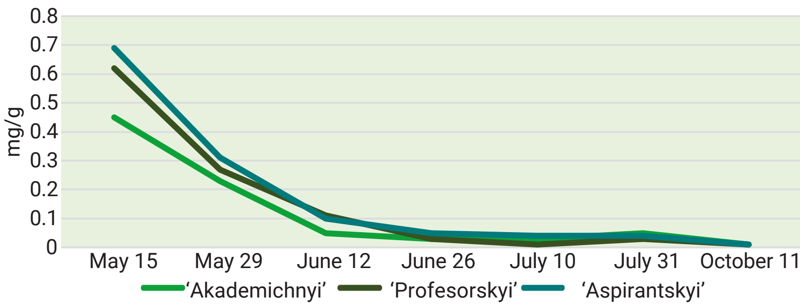


Figure 6. Dynamics of anthocyanin content in leaves of the best hazel genotypes during the growing season, 2023

Source: compiled by the authors

Chalcones, which belong to the class of flavonoids along with anthocyanis, are substances involved in the secondary metabolism of plants. As pointed out by Y.N. Nayak *et al.* (2022), chalcones have low biological activity. However, they exhibit antibacterial, antifungal, antitumor, and anti-inflammatory properties. According to L.M. Shevchuk (2019), chalcones, along with anthocyanins are components of the polyphenol complex in the fruits of many crops. Similar to other pigments, the highest chalcone content in leaves was observed at the beginning of the growing season, with values of 1.24 mg/g in green-leaved and 1.21 mg/g in purple-leaved hazel, respectively (Fig. 5). It then decreased but remained at about the same level throughout the growing season. No statistically significant difference in chalcones content was found between the two groups of hazel studied.

Morphometric characteristic of the best selections. The aim of introduction and breeding effort is to select well-adapted forms exhibiting a complex of economically valuable characteristics. In the population of hybrid purple-leaved hazel seedlings exhibits significant variability in yield, ripening time and fruit quality. Thus, the nuts display a wide range of characteristics. Their shape varies from very elongated and almost cylindrical to ovoid and conical. They also differ in size (from small to large), ripening time (from early to late), shell thickness, and degree to which the fiber develops around the kernels. Based on a comprehensive evaluation of their characteristics, varietal names were assigned to the three best seedlings (Fig. 7).

Morphometric data of nuts from these best genotypes are presented in Table 1.

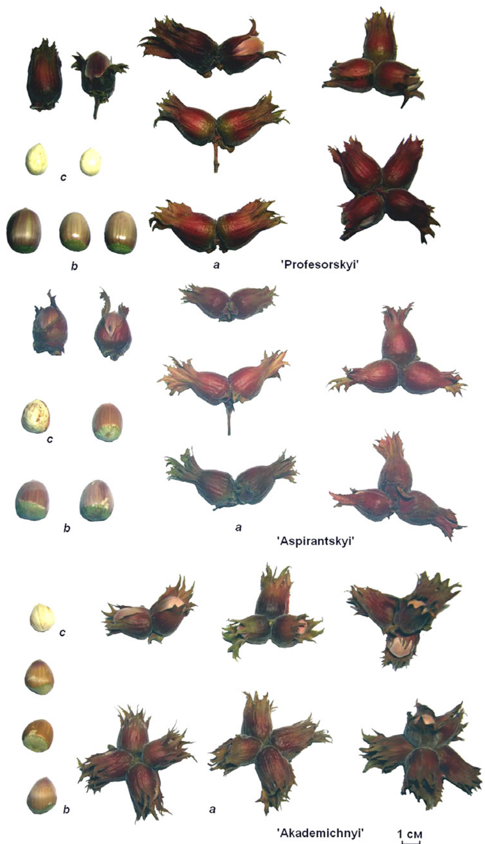


Figure 7. Fruits of the best hazel genotypes

Note: a – fruits with involucre; b – nuts; c – kernel without pelicula
Source: authors' photo

Table 1. The morphometric characteristics of the best hazel genotypes nuts, 2023-2024 (x ± SD, n = 20)

Traits	'Profesorskyi'	'Aspirantskyi'	'Akademichnyi'
Average weight, g	3.20 ± 0.35 a	2.75 ± 0.28b	2.47 ± 0.25c
Kernel percentage, %	47.96 ± 3.39b	50.99 ± 3.77a	51.74 ± 2.98a
Shell thickness, mm	1.13 ± 0.11a	1.09 ± 0.06a	1.12 ± 0.10a
Nut height, mm	25.60 ± 0.98a	23.23 ± 1.28b	22.28 ± 1.04c
Nut diameter, mm	18.65 ± 1.44a	17.50 ± 0.93c	16.52 ± 1.04c
Shape index	1.38 ± 0.09a	1.33 ± 0.09b	1.35 ± 0.08ab

Note: different letters indicate values that are significantly different within one row according to results of the Tukey's test ($P \leqslant 0.05$)
Source: compiled by the authors

'Profesorskyi' has the largest nuts, weighing more than 3 g. 'Aspirantskyi' and 'Akademichnyi' have nut weights of 2.7-2.8 g and 2.3-2.6 g, respectively. The purple-leaved hazelnut cultivars 'Bahrianyi' and 'Barbakan' registered in Ukraine have an average nut weight of 4.60 g (Bahrianyi, 2022) and 2.43 g (Barbakan, 2021), respectively. However, despite its large nuts, 'Bahrianyi'exhibited a lower kernel percentage compared to all three best-selected genotypes. Similarly, 'Barbakan' demonstrated a lower kernel percentage than the selected genotypes. The shells are thin and easily split in these best genotypes. The kernels of 'Profesorskyi' and 'Aspirantskyi' exhibit an absence or only a very weak presence of the fiber. Based on the weight, length, and diameter of the nuts, the selections are arranged in descending order: 'Profesorskyi' > 'Aspirantskyi' > 'Akademichnyi'. In all these genotypes, the nut length exceeds the nut diameter.

Environmental factors. Over 10 years of observation, purple-leaved hazel plants showed no damage from winter frost or spring frosts. During prolonged summer droughts with no precipitation and high air temperatures, adult hazel bushes grown on rainfed soils showed no obvious signs of leaf damage. The plants exhibit excellent growth, and self-seeding occurs under the bushes. Taking into account all these indicators, the degree of acclimatisation is determined as 100% (Kokhno & Kurdyuk, 1994). Aphids, some caterpillars, and true weevils were observed on the leaves. However, these phytophagous pests did not exceed the economic damage threshold. The percentage of nuts affected by the hazel weevil (*Curculio nucum* L.) in the absence of chemical control of the pest reaches 10-12%.

Powdery mildew negatively affects the appearance of hazel leaves (Fig. 8a). *Phyllactinia suffulta* is the type species of the genus causing this disease and is considered a synonym of *Phyllactinia guttata* (Wallr.) Lév. (Cooke, 1952). *Phyllactinia guttata* (*Helotiales, Ascomycota*) is considered a species complex that requires a comprehensive morphological and molecular revision. The fungus parasitizes a wide range of deciduous trees and a smaller number of herbaceous plants. In addition to hazel, this powdery mildew fungus affects fruit crops such as quince, grape, pear, cornelain cherry, kiwi, pistachio, mulberry, and forest trees such as birch, beech, alder, elm, and robinia (Hartney *et al.*, 2005). In Ukraine, common hazel is often affected by powdery mildew caused by *Phyllactinia guttata*. The mycelium of this fungus initially develops endophytically, in the mesophyll of the leaf. Only in late summer does it grow through the stomata to the lower surface of the leaf. Here the mycelium forms the conidial stage of the fungus and later produces fruiting bodies called chasmothecia. During these two stages, the fungus is easy to spot because it forms large, grayish patches that can coalesce into a continuous mycelial layer. Apparently, this disease does not cause significant damage to the host, as it only develops intensively in the fall, at the end of the plant's growing season (Heluta *et al.*, 2019). However, the appearance of the leaves affected by the disease has an adverse effect on the overall decorative effect.

a

b

Figure 8. Hazel leaf lesions

Note: a – Phyllactinia guttata (upper side of the leaf blade), b – Erysiphe corylacearum (lower side of the leaf blade), 2024

Source: authors' photo

A recently discovered species of powdery mildew fungus, *Erysiphe corylacearum* U. Braun & S. Takam. (*Erysiphales, Ascomycota*), has been identified in Ukraine. This species, native to East Asian and North America, has already been documented in Kyiv, Prykarpattia, and Crimea. It is postulated that the fungus migrated from the east or southeast, traversing the Caucasus. Given the epiphytic nature of *Erysiphe corylacearum* in Iran and Turkey, its widespread distribution in Ukraine is anticipated. This has the potential to cause significant damage to ornamental plantations and result in substantial losses in hazelnut farms (Heluta *et al.*, 2019; Heluta & Fokshei, 2020). Hazel leaves damaged by this species of powdery mildew are shown in Figure 8b.

V.P. Heluta *et al.* (2019) and V.P. Heluta & A.I. Fokshei (2020) reported the first occurrences of *Erysiphe corylacearum* in Ukraine, describing its spread as an invasive species affecting hazel trees. Their findings indicated that this alien fungus posed a threat to hazel plantations due to its rapid adaptation to local climatic conditions and its ability to cause extensive powdery mildew infections on leaves. These results highlighted the critical need for continuous monitoring of hazel plantations in Ukraine. S. Hartney *et al.* (2005) identified significant fungal pathogen *Phyllactinia guttata*, which was as the causal agent of powdery mildew in *Corylus avellana* in Washington State. Their study emphasised the importance of early detection and control strategies due to the negative impacts or this pathogen on the growth and physiological functions of infected trees. The presence of *Phyllactinia guttata* in North America suggests its potential expansion to other regions, making it a relevant concern for global hazelnut cultivation.

These studies provide a foundation for understanding the phytopathological risks associated with hazel cultivation and the nutritional significance of its fruits. However, further research is needed to explore the resistance mechanisms of hazel trees against fungal pathogens and the impact of environmental stressors on their biochemical composition. This study aims to address these issues by analysing the introduction of purple-leaved hazel in the Forest-Steppe of Ukraine and evaluating its morphological, physiological, and resistance characteristics.

The research showed that the visual difference between green- and purple-leaved hazelnuts was due to the accumulation of a significant amount of anthocyanidins in the latter. Concurrently, there was no significant difference in the content of other pigments. Among the hybrid population, three genotypes with high-quality nuts, competitive with registered varieties, were selected. Their adaptability to the growing region provides a good basis for wider testing and introduction into forest restoration, ornamental, and orchard plantations.

Conclusions

This study was conducted to highlight the characteristics of a new purple-leaved hazel selections developed at the National University of Life and Environmental Sciences of Ukraine. The purple-leaved hazels have been cultivated in the Ukraine for ornamental purposes on a limited scale for over a century, and two nut varieties have been registered in recent years. The three new best genotypes exhibit certain morphological and physiological differences from the typical green-leaved hazel and characterised by high ornamental value due to their intensely coloured leaves in the first half of the growing season, followed by beautifully coloured fruit shells. The highest content of anthocyanins (average of 0.59 mg/g) and chalcones (average 1.21 mg/g) in leaves was found in mid-May. The highest content of chlorophyll a (average 2.39 mg/g), chlorophyll b (average 1.29 mg/g), and carotenoids (average 0.58 mg/g) was found in early July. The varieties 'Profesorskyi', 'Aspirantskyi' and 'Akademichnyi have large nuts with an average weight of 3.2 g, 2.8 g and 2.5 g, with a high kernel percentage of 48.0%, 51.0% and 51.7%, respectively. Based on these indicators, their performance is comparable to or exceeds that of registered purple-leaf hazelnut cultivars in Ukraine. A new species of powdery mildew fungus was detected, which has recently begun to spread in Ukraine. The varieties are well adapted to the soil and climatic conditions of the Forest-Steppe of Ukraine and can be used in forest restoration plantations, landscaping and gardening. The genotypes developed are valuable for further breeding work and will be the subject of a wider range of studies, including reproduction and fruit biochemical composition.

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Conflict of Interest

None.

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Анотація. Дане дослідження проведено в 2023-2024 рр. з метою з’ясування походження та інтродукції пурпуроволисткової ліщини, а також вивчення морфологічних і фізіологічних особливостей кращих генотипів, створених авторами. Було проведено морфометричний аналіз горіхів, кількісний та якісний склад пігментів в листках в динаміці та спостереження за впливом абіотичних та біотичних чинників довкілля. Виявлено, що у *Corylus* існують мутанти з червоним/фіолетовим забарвленням оболонки ядра та/або листків. Їх неодноразово знаходили в різних місцях Європи, відносячи до видів *Corylus avellana* та/або *Corylus maxima*. Систематики вважають ці таксони окремими, проте молекулярні дослідження свідчать, що *Corylus maxima* слід синонімізувати з *Corylus avellana*. Найкращі селекційні зразки пурпуроволисткової ліщини характеризувалися високоякісними горіхами масою 2,5-3,2 г та з виходом ядра 48,0-51,7 %. Встановлено, що за вмістом хлорофілу a, хлорофілу b, каротиноїдів та антоціанів пурпуроволисткові добори ‘Професорський’, ‘Аспірантський’ і ‘Академічний’ перевищують зеленолисткові сорти, хоча ця різниця не є статистично значущою у більшості випадків, за винятком антоціанів. Високий вміст антоціанів у листках (до 0,69 мг/г у травні) та у плюсках надавав цим генотипам виняткової декоративності протягом першої половини вегетації та пізніше. Ці генотипи мали високу зимостійкість та посухостійкість і добре адаптовані до місцевих ґрунтово-кліматичних умов. Серед біотичних факторів довкілля негативний вплив мали ліщиновий довгоносик *Curculio nucum* (пошкоджував горіхи) та борошнистий гриб *Phyllactinia guttata* (вражав листки). На листках також було виявлено новий для України борошнисторосяний гриб *Erysiphe corylacearum*. Ці результати підтримують ширшу інтродукцію пурпуроволисткової ліщини, оскільки найкращі генотипи мають високу декоративність, а також дають горіхи. Отримані дані будуть корисними для лісомеліорації, декоративного та аматорського садівництва

Ключові слова: *Corylus avellana;* декоративні рослини; антоціани; маса горіха; відсоток ядра; борошниста роса

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Properties of heat-treated ash wood

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Abstract. Ash wood is characterised by high mechanical and technological properties and has a beautiful texture, which leads to a high demand for furniture and joinery products made from it. However, the widespread and rapid spread of the fungal disease *Hymenoscyphus fraxineus* (chalar necrosis) and the invasive beetle *Agrilus planipennis* caused massive dieback of ash trees. All of this led to the transformation of healthy wood during one year into low-quality "deadwood" and limited its use in industry. The objective of the research was to investigate specific properties of ash deadwood subjected to sterilisation through high-temperature treatment using various thermal regimes. To renew its use, it is proposed to use sterilisation without the addition of chemicals by thermal modification at temperatures of 185 °C (schedule 1) and 195 °C (schedule 2), which does not impair the environmental properties of wood. The physical, mechanical, and technological properties of heat-treated 'deadwood' ash and healthy wood dried at a temperature of t ⩽ 70 °C were studied. It has been determined that the equilibrium moisture content of heat-treated 'deadwood' ash wood decreased by 3.5-4.0% compared to healthy wood; the density at actual moisture and in a completely dry state decreased by 8-12% and by 4-9%, shrinkage in the transverse direction by 53-67%; the bending strength decreased by only 6% in the case of schedule 1 and by 20% in the case of schedule 2. The static hardness in both the tangential and radial directions had an unexpected trend – an increase of 9-12% when using schedule 1 and a decrease of 1.7-13% when treated by schedule 2. The weight loss of samples of heat-treated 'deadwood' ash wood was 60-90% less than the weight loss of healthy wood. The accuracy factor of all experimental studies did not exceed 5%. The results obtained make it possible to effectively choose the use of heat-treated 'deadwood' ash wood under schedule 1 in joinery and furniture products, and treated under schedule 2 in furniture products such as tabletops, as there is a decrease in the relevant mechanical properties. The use of both treatment modes allows the use of low-cost ash wood in products that are used outdoors

Keywords: 'deadwood'; heat treatment; physical properties; strength; hardness; biostability

Introduction

The current environmental crisis, including climate change, has a significant impact on forests. Massive dieback of trees, in particular, of the ash (*Fraxinus excelsior*), caused by the fungal disease *Hymenoscyphus fraxineus* (chalar necrosis) and the invasive emerald ash borer (*Agrilus planipennis*), was recorded in a number of European countries as early as 2002. In Ukraine, since 2019, ash trees have been affected by halar necrosis and emerald ash borer, which makes the trees susceptible to infestation by the ash tree beetle *Hylesinus spp*. It is believed that the fungus *Hymenoscyphus fraxineus* may have entered Western Ukraine from Poland as early as 1994 (Davydenko *et al.*, 2022).

M. Pugovytsia (2020) established that a characteristic appearance of chalara necrosis is the death of individual branches and further drying out of the tree. The first sign of an ash tree infection with this fungus is the appearance of white spots on the leaves or 'deadwood tops'. Despite extensive research, no effective way to combat the fungus has yet been found. Moreover, according to scientists, there are currently about 2 million km^2 of infected trees in Europe. The other threat is the emerald ash borer, for which ash has become an ideal breeding ground.

The larvae of the beetle penetrate the tree trunk and feed on its sap, and the speed of spread of this pest is impressive – 41 km per year. These pests are leading to large-scale dying of forests in Europe, increasing the amount of so-called 'dead wood'. In addition, such wood is often infected with wood-staining fungi, which creates difficulties for its use in industry.

Studies of ash tree mortality across various geographical locations, including England, Scandinavia, and the Baltic States, have provided valuable insights into the long-term effects of Chalara dieback (*Hymenoscyphus fraxineus*) on European ash (*Fraxinus excelsior*). Research has shown that the disease leads to high mortality rates, with regional variations influenced by climate, forest management practices, and the genetic resilience of local ash populations. For instance, long-term monitoring in Latvia recorded a maximum mortality rate of 69.4% in 2017, reflecting the devastating impact of the pathogen on ash populations in the Baltic region (Davies, 2017). Similarly, studies in Denmark have shown even more severe consequences, with up to 90% of ash trees being lost due to the disease (Coker *et al.*, 2022). These findings align with broader European trends, where mortality rates continue to rise as the pathogen spreads and trees experience progressive decline. While some individual trees have demonstrated tolerance or partial resistance, large-scale losses threaten the ecological and economic value of ash woodlands. T. Coker *et al.* (2018) highlighted the need for conservation efforts and breeding programmes to enhance resistance within ash populations, as well as adaptive forest management strategies to mitigate the ongoing decline.

As the share of affected ash wood increases every year, the question is raised as to the need for its efficient and rational use in industry. One of the most promising approaches to improving the quality of ash 'dead wood' is its sterilisation. The European standards UNE EN 113-1:2021 (2021) and UNE EN 113-2:2021 (2021) recommend the use of such methods of sterilisation of damaged wood as steam treatment, gamma irradiation and ultra-high frequency current. The use of gamma irradiation and microwave insecticide has a positive effect, but the equipment for their implementation is quite expensive. In addition, the latter method is used mainly for disinfection of finished products during restoration (Appiah-Kubi *et al.*, 2021; Brischke *et al.*, 2022). The most common and environmentally friendly treatment is wood heating.

The Ministry of Agrarian Policy and Food of Ukraine regulates phytosanitary measures for wooden packaging material, which involve heating wood to a temperature of 56 °C for at least 30 minutes (Pyvovarov, 2024). Similar recommendations were given in the work by D. Jones *et al*. 2019). For complete sterilisation of wood, higher temperatures are used – over 110°C (Candelier & Dibdiakova, 2020), which leads to its thermal modification.

H. Pleschberger *et al*. (2014) researched that thermal modification of wood occurs when the material is heated in the temperature range of 120-240°C. This causes the wood to become a richer, darker colour, which creates the effect of expensive woods such as walnut or mahogany. This change can effectively hide the effects of fungal infestation, which is common in 'dry wood', giving the material a uniform appearance and masking possible stains or discoloured areas. In addition to masking defects, the heat treatment process increases the aesthetic appeal of wood, as the new colour makes it visually richer, which is especially appreciated in furniture production, decorative panels, flooring and other interior elements. Most thermal modification processes, even at moderate temperatures, reduce the hygroscopicity of wood, i.e. its ability to absorb moisture from the air. As a result of the loss of hygroscopic hemicellulose polymers during thermal modification, the equilibrium moisture content decreases, and swelling and shrinkage are reduced accordingly. According to B. Marcon *et al*. (2022), this leads to improved dimensional stability and resistance to biodegradation. On average, the equilibrium moisture content is reduced to about half the value of untreated wood. The hygroscopicity of thermally modified wood can vary significantly depending on the process parameters.

G. Milić *et al*. (2023) noted that the process of thermal modification of wood leads to a decrease in its density and mass, and the higher the modification temperature, the greater the decrease in these properties. Moreover, a greater decrease in wood density and its mass was observed for samples with a higher density and at a higher processing temperature. According to G. Milić *et al*. (2023), thermal modification affects the anatomical structure of wood, the chemical composition and structure of the wood cell wall change at the molecular level. Chemical reactions can be activated inside the cell walls at high temperatures: hydrolysis of acetyl groups in xylans produces acetic acid; hemicelluloses depolymerise into oligomeric and monomeric links without increasing crystallinity and further dehydrate to aldehydes in acidic conditions, which leads to less hydroxyl groups and lower hygroscopicity; lignin, as the most inactive component, can be broken down to form phenolic groups. S. Amirou *et al*. (2019) noted that thermally modified wood gets a more porous structure with an increase in the number and size of pores.

According to J.F. Herrera-Builes *et al*. (2021), compared to untreated wood, thermally modified wood becomes more fragile, showing lower strength in bending, compression and tension, which limits its use in engineering structures This was explained by a decrease in weight, degradation of hemicellulose. However, the study of the effect of different temperatures on the mechanical properties of pine (*Pinus oocarpa*) by H. Pleschberger *et al*. (2014) detected an increase in mechanical properties and, according to the authors, it is associated with cross-linking of the lignin network and cellulose rearrangement and crystallisation, which strengthen the middle layer. This led to the idea of using thermally modified pine (*Pinus oocarpa*) wood in engineering products.

Despite some contradictions in the results of the study of the mechanical properties of thermally modified wood by J.F. Herrera-Builes *et al.* (2021), the use of elevated processing temperatures for sterilisation of dry wood affected by pests is relevant, as the absence of sugars (hemicelluloses) and a significant amount of moisture necessary for the survival of fungi increase its biostability. In addition, the heat treatment process does not add any chemicals to the wood and is an environmentally friendly alternative to metal-based preservatives used to protect wood.

The rapid growth in the production of thermally modified wood due to improved biological stability furniture, dimensional stability, and thermal conductivity has led to its use for building facing, decking, joinery, and products used indoors, such as floors, panels, furniture (Scheiding *et al*., 2022).

The aim of the study was to determine some properties of ash ‘dead wood’ sterilised by treatment under high temperatures in different schedules. To achieve this aim, the following tasks were set:

- to determine the values of actual moisture content, equilibrium moisture content, density and shrinkage of heat-treated ash ‘dead wood’ by different schedules;

 to determine the values of the static bending strength, hardness and stability in soil of heat-treated ash 'dead wood' by different schedules.

The scientific novelty is to determine the possibilities of using heat-treated ash 'dead wood' in furniture and joinery products.

Materials and Methods

For the study, samples of ash wood the first year's decay, 'dead wood' heat-treated at 185°C – schedule 1 and 195°C – schedule 2 for 40 hours, as well as samples of unaffected ash wood dried at a temperature of t ⩽ 70°C were used as control samples (C). All samples (total 310 samples) had a clear orientation of the annual layers (tangential or radial) in cross-section. The method of DSTU 4922:2008 (2009) was used to determine the actual moisture content of the samples. The actual moisture content, W, %, was calculated by the formula:

$$W = \frac{m_1 - m_0}{m_o} 100\%, \quad (1)$$

where m_1 – mass of the sample before drying, g; m_0 – mass of the absolutely dry test sample, g. To determine the equilibrium moisture content of ash wood, the method P. Mitchell (2018) was used, according to which the samples were dried to absolutely dry moisture (W = 0%) and then kept indoors for 50 days. The samples were weighed periodically. The test was considered complete when the samples stopped changing weight. The moisture content, W_p, %, was calculated using the formula:

$$W_p = \frac{m_f - m_0}{m_o} 100\%, \quad (2)$$

where m_f – mass of the sample after aging for 50 days, g; m_0 – mass of the absolutely dry test sample, g. The density of the samples at actual moisture content, ρ_w, g/sm^3 was determined and calculated according to DSTU EN 408:2007 (2009):

$$\rho_w = \frac{m_w}{V_w}, \quad (3)$$

where m_w – sample mass at actual moisture content, g; V_w – sample volume at actual moisture content, sm^3. To determine the density of absolutely dry samples, ρ_0, g/sm^3, was used the formula:

$$\rho_0 = \frac{m_0}{V_0}, \quad (4)$$

where V_0 – sample volume in an absolutely dry state, sm^3. The shrinkage of the samples was determined according to the method of ISO 4469:1981 (1982). The following formulas were used to calculate the amount of shrinkage in the tangential, β_t, %, and radial, β_r, %, directions:

$$\beta_t = \frac{a_{t_W} - a_{t_0}}{a_{t_W}}, \quad (5)$$

$$\beta_t = \frac{a_{t_W} - a_{t_0}}{a_{t_W}}, \quad (6)$$

where a_{tW}, a_{rW} – dimensions of samples at actual moisture content in the tangential and radial directions, mm, a_{t0}, a_{rW} – dimensions of samples at absolutely dry moisture content in the tangential and radial directions, mm. To determine the static bending strength, we used the method described in ISO 13061-3:2014 (2014). The strength was calculated using the formula:

$$\sigma_w = \frac{3P_{max} l}{2bh^2}, \quad (7)$$

where σ_w – tensile strength of the sample at actual moisture content, MPa; P_{max} – maximum load, N; *l* – distance between the centres of the supports, mm; *b, h* – sample height and width, mm. The bending strength at three-point loading was determined using a universal testing machine P5 (LTD "ASMA-PRYLAD", Ukraine) (Fig. 1).

Figure 1. Visualisation of tests of samples to determine the static bending strength
Source: compiled by the authors

The static hardness was determined by the method of the recovered impression of a depressed spherical indenter according to ISO 13061-12:2017 (2017). The calculation of the hardness of the samples, H_w, N/mm^2, at actual moisture content was determined by the formula:

$$H_w = \frac{P}{\frac{\pi D}{2} \cdot \left(D - \sqrt{D^2 - d^2}\right)}, \qquad (8)$$

where P – applied load, kPa; D – ball diameter, mm; d – print diameter, mm. The stages of determining the static hardness of ash wood samples in the tangential and radial directions by the method of the depressed spherical indenter are shown in Figure 2. The results of indentation on different samples are shown in Figure 3.

Figure 2. Visualisation of static hardness tests of ash wood samples
Source: compiled by the authors

a *b* *c*

Figure 3. Imprints of the indenter on ash wood samples
Note: a – control samples C; b – samples treated by schedule 1, c – samples treated by schedule 2
Source: compiled by the authors

The determination of wood stability in soil conditions was determined by the loss of their mass after placing control samples and thermally modified samples of ash ‘dead wood’ in a special container for 60 days (Sirko *et al.*, 2024). The mass loss of the samples, Δm, %, was calculated by the formula:

$$\Delta m = \frac{m_{01} - m_{02}}{m_{01}} 100\%, \qquad (9)$$

where m_{01} – mass of the sample in an absolutely dry state before placing it in a container with soil, g; m_{02} – mass of the sample in an absolutely dry state after placing it in a container with soil, g. To determine the stability of wood in soil conditions, ash wood samples dried to an absolutely dry state (Fig. 4a) were stored in soil (Fig. 4b). The soil moisture content was maintained at 60-70% by periodic moistening.

The number and dimensions of the test specimens for one series of tests, due to the methods used, are given in Table 1.

a *b*

Figure 4. Placement of samples for decay resistance testing

Note: a – drying ash wood samples to an absolutely dry state in a thermostat at a temperature of 103 ± °C; b – holding ash wood samples in a container with soil
Source: compiled by the authors

Table 1. General characteristics of test areas

The property under study	Sample dimensions, mm	Quantity, pcs.
Actual moisture content	20 × 20 × 30 (length)	25
Equilibrium moisture content	20 × 20 × 30 (length)	25
Density of the samples at actual and absolutely dry moisture content	20 × 20 × 30 (length)	16
Shrinkage in the transverse direction	20 × 20 × 30 (length)	16
Static bending strength	20 × 20 × 300 (length)	35
Static hardness	20 × 20 × 150 (length)	23
Stability of wood in soil conditions	20 × 20 × 5 (length)	15

Note: dimensions and number of test specimens
Source: developed by the authors

Accordingly, three times as many samples were used for the study, taking into account the treatment schedule of ‘deadwood’ and unaffected wood. To determine the actual and equilibrium moisture content, the samples were weighed (Fig. 5a), then placed in a laboratory drying oven SNOL67|150 LTD “TermoLab”, Ukraine (Fig. 5b) and dried at 103 ± 2°C to a constant weight. The actual moisture content of the samples was calculated using formula (1).

a *b*

Figure 5. Example of weighing (a) and drying of test samples (b)
Source: compiled by the authors

Results and Discussion

The actual moisture content of the samples was calculated using formula (1). The results of determining the actual moisture content of the samples are shown in Figure 2, which shows that the heat-treated wood had almost 3-4 times less moisture. Similar results were obtained C. Hill *et al.* (2021) when determining the moisture content of different species of wood, indicating the removal of not only adsorption moisture, but also chemically bound and decomposition of anatomical elements. After storing the absolutely dry samples in a room with the following climatic parameters: temperature t = 22°C, relative humidity φ = 65%, their equilibrium moisture content was calculated using formula (2). The calculation results are shown in Figure 6.

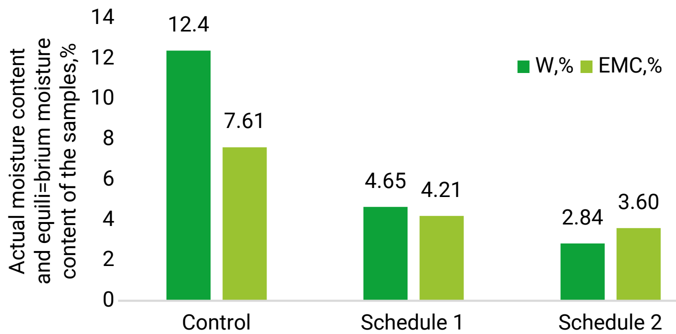

Figure 6. Results of determining the actual and equilibrium moisture content of ash samples
Source: compiled by the authors

There is a significant decrease in the equilibrium moisture content of heat-treated wood by almost 50%, which is consistent with the results of numerous studies conducted on different species of wood (Candelier & Dibdiakova, 2020; Hill *et al.*, 2021). This is due to a change in chemical properties when wood is exposed to high temperatures, which leads to a decrease in the hygroscopicity of wood. The results of determining the density of ash samples at actual moisture content and in an absolutely dry state are shown in accordance with formulas (3) and (4) in Figure 7.

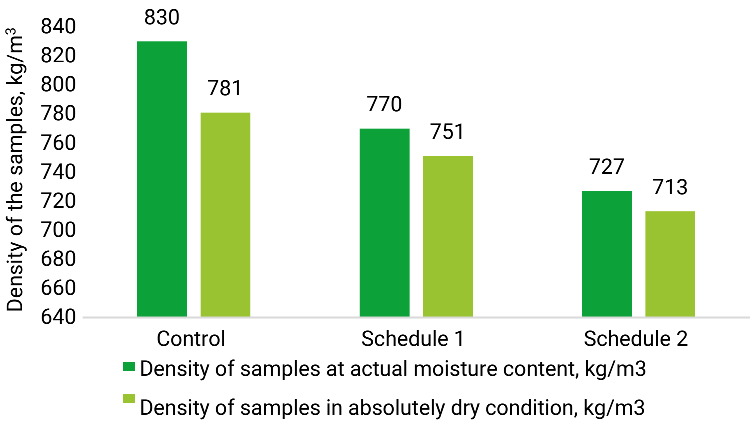

Figure 7. Density values of ash wood samples at actual moisture content and in an absolutely dry state

Source: compiled by the authors

The results obtained are consistent with those of previous researchers G. Milić *et al*. (2023), which were carried out on other wood species, but have a similar tendency to decrease in density when high processing temperatures are used, as this leads to changes in the morphological, chemical and physical properties of the wood cell wall. The amount of shrinkage of the samples in the tangential and radial directions was calculated using formulas (5-6), and the visualisation of the property changes depending on the heat treatment is shown in Figure 8.

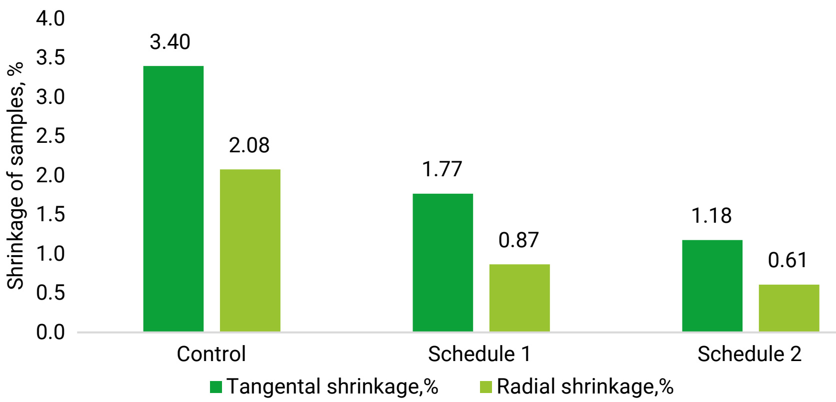

Figure 8. The amount of shrinkage of ash samples in the tangential and radial directions

Source: compiled by the authors

According to S.Y. Zhang *et al*. (2021) the amount of wood shrinkage directly depends on its density, decreasing with decreasing density. The same tendency is observed in the case of heat treatment of wood (Xu *et al*., 2019; Nhacila *et al*., 2020). The average values of the tensile strength of the tested samples calculated by (7) are shown in Figure 9.

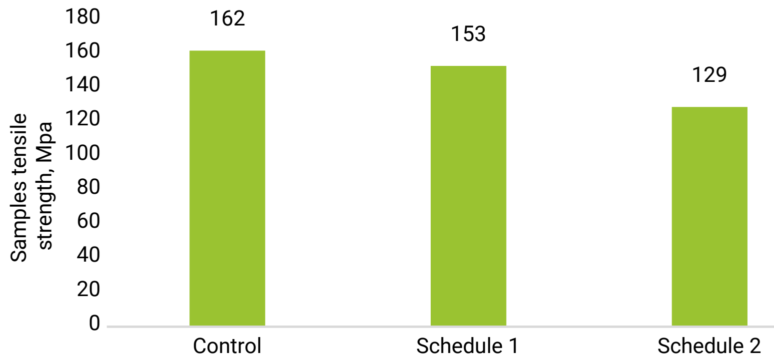

Figure 9. Tensile strength values of ash wood samples
Source: compiled by the authors

In the case of heat treatment under schedule 1, a minor decrease in strength was observed – only 6%. The insignificant decrease in strength was probably due to the connection of lignin fibres and cellulose crystallisation under the influence of elevated temperature. Similar results were obtained in C. Hill *et al*. (2021) when determining the mechanical properties of heat-treated *Pinus oocarpa* wood at a processing temperature of 170°C. The authors believe that such wood can be used for construction purposes. The results of calculation of static hardness are shown in Figure 10.

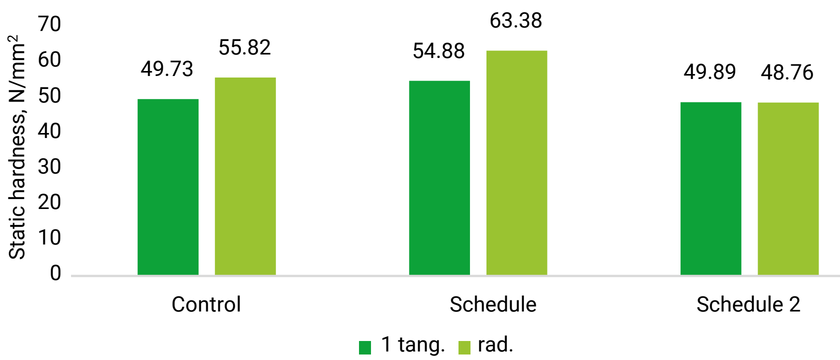

Figure 10. Hardness values of ash wood samples
Source: compiled by the authors

The hardening of microfibres due to cellulose crystallisation at high temperatures, as well as an increase in the relative proportion of lignin (Hill *et al*., 2021) during the processing of ash wood, almost did not reduce its hardness, which also adds weight to the above statement about the possibility of using thermally modified wood in some structural products. Information on a similar situation with the hardness of wood, even when treated at a temperature of 200°C, is given in the works by W. Moliński *et al*. (2016) and G. Milić *et al*. (2023). The results of calculating the mass loss of ash wood samples according to (9) are shown in Figure 11.

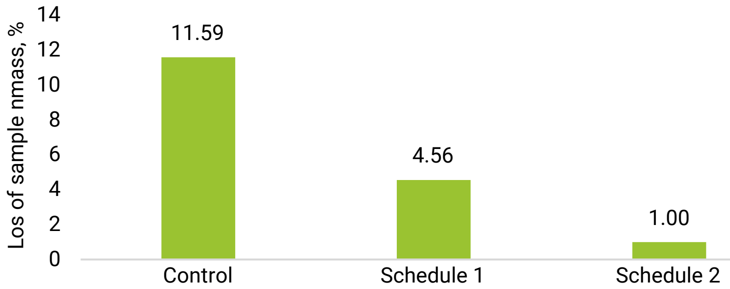

Figure 11. Average mass loss values of ash samples

Source: compiled by the authors

The positive effect of thermal modification of ash wood on biostability is visible, which is characterised by a significantly lower mass loss (2.5 times – 11.5 times, depending on the treatment temperature) compared to untreated ash 'dead wood'. A small mass loss (< 2%) of samples of fungus-infested plywood made of birch and beech wood after heat treatment at 215°C was observed in the work by J.B. Paes *et al.* (2021). This is consistent with the results of current studies. Based on the results of the tests, the following statistical characteristics were determined: standard deviation (± S), coefficient of variation (V, %), accuracy (P, %) for control samples (C) and samples treated at a temperature of t = 185°C (1) and t = 195°C (2). The average values of the obtained characteristics for different types of tests are given in Table 2.

Table 2. Average values of statistical characteristics

Type of test	± S			V, %			P, %		
	Schedules								
	C	1	2	C	1	2	C	1	2
Equilibrium moisture content, %	0.1	4.21	0.12	1.32	13.6	3.23	0.33	3.4	0.1
Actual moisture content, %	0.28	0.3	0.43	2.27	6.38	!5.1	0.57	1.6	3.8
Density of the samples at actual moisture content, kg/m^3	2.8	26.2	18.1	0.33	3.4	3.9	0.08	0.85	0.97
Density of the samples at absolutely dry moisture content, kg/m^3	3.3	28.1	23.2	0.42	3.75	3.25	0.1	0.94	0.81
Shrinkage in the transverse direction, %	0.06	0.05	0.04	2.36	3.55	4.66	0.59	0.89	1.16
Static bending strength MPa	14.6	39.9	28.1	9.0	16.0	21.8	1.52	4.34	3.69
Static hardness, N/mm^2	8.5	7.9	11.0	15.9	13.1	22.6	3.3	2.7	4.7
Stability of wood in soil conditions- mass loss, %	2.0	0.7	0.1	17.2	15.3	6.9	4.3	3.8	1.8

Source: compiled by the authors

The obtained data on the physical and mechanical properties of thermally modified ash 'deadwood' are quite reliable (the accuracy rate does not exceed 5%) and allow us to confirm that the applied sterilisation allows its use in various products both indoors and outdoors. Depending on the treatment regime and the experience of using heat-treated wood of other species (Pinchevska *et al*., 2019; 2022) facture of furniture and joinery. This will help preserve the environment and help to implement new design solutions in joinery and furniture made of heat treatment ash 'deadwood', which has an attractive texture and good physical and mechanical properties.

Significant deterioration of ash due to the influence of pests makes it impossible to use its valuable and aesthetically pleasing wood for the manufacture of furniture and other products. Sterilisation of the affected wood by thermal modification is proposed, which is safe for the environment and gives new properties to the "deadwood" ash. High-temperature treatment changes the chemical structure of wood, in particular, affects the cell walls, which causes a decrease in its density, moisture content and hygroscopicity, and increases its form stability due to reduced shrinkage. Studies have shown that these changes were most pronounced at 195°C (schedule 2). However, due to the reduced strength of wood at high temperatures, schedule 1 is a higher priority, since its effect on strength is almost imperceptible. In addition, an increase in the hardness in the radial direction was observed in this mode, which is probably due to the crystallisation of cellulose. This confirms the possibility of using ash wood processed under schedule 1 for structural elements of furniture, in particular for the manufacture of chairs. The high bio stability of the modified wood also allows it to be used for the production of garden furniture. The obtained research results are consistent with the data of other scientists who have studied the properties of thermally modified wood of various species.

Conclusions

The results of the studies on the possibility of using "deadwood" ash wood affected by pests have shown that when it is sterilised by thermal modification, it acquires properties that allow it to be used in the manufacture of furniture and joinery. Experimental studies of moisture content, density and equilibrium moisture content were carried out in accordance with the methodology of national standards; the methodology of international standards was used to determine static bending strength and static hardness. A total of 310 samples of healthy and "deadwood" thermally modified ash were tested. It was found that the density of thermally modified "dead wood" decreased by 10% compared to healthy wood, which facilitates the production of solid wood products (furniture, panels, etc.). The studies of drying and equilibrium moisture content of thermally modified healthy and "deadwood" wood showed a significant, almost twofold decrease in these indicators for "deadwood" wood, which allows it to be used in the manufacture of joinery (windows, doors, etc.). The loss of bending strength by 9-33 MPa and virtually unchanged hardness in the radial and tangential directions makes it possible to use such wood in some structural elements of furniture. Studies of the biological stability of thermally modified healthy and "deadwood" ash wood have shown that weight loss decreased by 2.5-11 times depending on the treatment regime, which facilitates the use of products outdoors. The results of the studies with an accuracy rate of less than 5% showed that the use of "deadwood" ash affected by pests in the case of its sterilisation under high temperature is possible for use in industry

In the future, it is planned to investigate the effect of UV radiation on the colour change of thermally modified ash wood and to identify rational finishing materials and adhesives that will improve the properties of products used outdoors.

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Conflict of Interest

None.

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Властивості термообробленої деревини ясена

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Анотація. Деревина ясена характеризується високими механічними та технологічними властивостями, має красиву текстуру, що зумовлює високий попит на меблеві та столярні вироби з неї. Проте широке та стрімке розповсюдження ураження грибковим захворюванням *Hymenoscyphus fraxineus* (халаровий некроз) та інвазійним жуком – смарагдовою вузькотілою златкою (*Agrilus planipennis*) викликало масове усихання ясенів. Все це призвело до перетворення протягом року здорової деревини у низькотоварну «сухостійну» і обмежило її використання у промисловості. Метою роботи було дослідити специфічні властивості сухостою ясена звичайного, підданого стерилізації шляхом високотемпературної обробки з використанням різних теплових режимів. Для поновлення використання запропоновано використання стерилізацію без додавання хімічних речовин шляхом термічного модифікування за температур 185 °C (режим 1) і 195 °C (режим 2), що не погіршує екологічних властивостей деревини. Проведені дослідження фізичних, механічних та технологічних властивостей термічно обробленої «сухостійної» деревини ясена та здорової деревини висушеної за температури t ≤ 70 °C. Визначено, що рівноважна вологість термічно обробленої «сухостійної» деревини ясена зменшилась на 3,5-4,0 % порівняно із здоровою деревиною; щільність за фактичної вологості та у в абсолютно сухому стані зменшилась на 8-12 % та на 4-9 %, усихання у поперечному напрямку на 53-67 %; межа міцності на згин зменшилась лише на 6 % у разі використання режиму 1 та на 20 % при використанні режиму 2. Статична твердість як у тангенціальному, так і радіальному напрямках мала неочікувану тенденцію - збільшення на 9-12 % при застосуванні режиму 1 і зменшення на – 1,7-13 % при обробці за режимом 2. Втрата маси зразків термообробленої «сухостійної» деревини ясена була на 60-90 % менше за втрату маси здорової деревини. Коефіцієнт точності усіх проведених експериментальних досліджень не перевищував 5 %. Отримані результати дають можливість ефективно вибирати застосування термообробленої «сухостійної» деревини ясена за режимом 1 у столярних і меблевих виробах, а обробленої за режимом 2 – у меблевих виробах, таких як стільниці, оскільки спостерігається погіршення відповідних механічних властивостей. Використання обох режимів обробки дозволяє використовувати низькотоварну деревину ясена у виробах, що експлуатуються просто неба

Ключові слова: «сухостійна» деревина; термічне оброблення; фізичні властивості; міцність; твердість; біостійкість

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Forest ecosystems in the context of a green economy: Potential for sustainable energy

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Abstract. The purpose of this study was to assess the potential for using wood biomass, including wood waste, as a renewable energy source for the energy sector of Kyrgyzstan, as well as to analyse its energy efficiency and environmental aspects. The study was conducted in two natural zones of the Kyrgyz Republic: mountainous (Naryn region) and lowland (Talas region). Field studies,

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laboratory methods, and statistical data processing were employed. The volume of wood in the study areas was determined by measuring the diameter and height of trees, with subsequent calculations using established formulas. The calorific value of wood from various species was analysed using the calorimetric method, and industry research data were used to estimate CO_2 emissions from the combustion of wood waste, coal, and natural gas. Statistical analysis, including the Student's t-test and analysis of variance (ANOVA), was performed to compare the energy potential of different fuel types. The results of the study indicated that Scots pine and English oak are the most promising types of wood for biofuel production in these regions. Calculations confirmed that chips and sawdust have the highest energy values, while wood bark has the lowest calorific value. Analysis of CO_2 emissions demonstrated that wood waste is a more environmentally friendly fuel compared to coal, although it is inferior to natural gas. The data obtained confirm the importance of the rational use of forest resources and the integration of wood waste into bioenergy as a means to reduce dependence on non-renewable energy sources and lower carbon dioxide emissions. The study revealed that the most promising types of wood for biofuel are Scots pine and English oak. The calorific value of chips was 9.5-10.8 GJ, sawdust – 10.2-11.5 GJ, while bark demonstrated the lowest values (8.3-9 GJ). CO_2 emissions from burning oak sawdust were 80 kg/GJ, wood chips – 90 kg/GJ, bark – 98 kg/GJ, while for pine these figures were higher: 85, 95, and 105 kg/GJ respectively. The analysis confirmed that wood waste is cleaner than coal but remains inferior to natural gas, which underlines its significance for bioenergy

Keywords: wood biomass; bioenergy; wood waste; CO_2; energy potential; renewable energy sources; sustainable development

Introduction

In the context of global environmental challenges and the need to transition to sustainable development models, the green economy is becoming an important area of energy policy. One of the key aspects of this approach is the search for alternative energy sources that can reduce dependence on fossil fuels and mitigate the negative impact on the environment. Forest ecosystems have significant potential in this context, as wood biomass and logging residues can be used as renewable energy resources. Wood waste, such as chips, sawdust, and bark, is considered a promising source of biofuels. Their use can not only reduce the volume of waste produced by the forest industry but also decrease carbon dioxide emissions during energy production when compared with traditional fuels such as coal.

However, for the effective implementation of biofuels, it is necessary to consider the regional characteristics of forest resources, their availability, and their energy potential. Researchers Z. Sakbaeva & N. Karabaev (2022), as well as G. Yusupova *et al.* (2023), have explored various aspects of Kyrgyzstan's transition to a green economy. In particular, Z. Sakbaeva & N. Karabaev examined issues related to the protection of the biosphere of walnut forests within the framework of the green economy, highlighting the need for an integrated approach to their conservation. In turn, G. Yusupova *et al.* analysed the role of water and energy resources in the development of a sustainable economic model for the country, considering the potential for their rational use. However, these studies focus more on a general understanding of the green economy and its individual components, while the use of wood biomass as an energy source within Kyrgyzstan's forest ecosystems remains insufficiently explored and requires further analysis.

K. Dzhumabaev *et al.* (2023) addressed the key issues in Kyrgyzstan's transition to a green economy, including barriers and prospects for the adoption of sustainable technologies. They emphasised the importance of state support and the adaptation of economic mechanisms for the efficient use of natural resources. In her study, O. Sabishchenko (2022) focused on the classification of renewable and non-renewable energy sources, analysing their potential and impact on environmental sustainability. These studies do not address the specific aspects of wood biomass utilisation in Kyrgyzstan's energy sector, highlighting the need for further research in this area.

Existing scientific research covers various aspects of using woody biomass for energy purposes, including its environmental benefits and economic efficiency. Particular attention is given to the analysis of the impact of biofuels on the environment, the potential for reducing greenhouse gas emissions, and the role of renewable resources in the transition to a green economy. At the same time, a number of key issues remain unresolved. In particular, these include the efficiency of using specific wood species, taking into account regional differences in forest composition, as well as the need for a comparative analysis of CO_2 emissions from the combustion of biofuels and traditional fuels (Aliaño-González *et al.*, 2022).

Thus, despite the existence of a significant number of studies on sustainable development, forestry, and renewable energy sources, the issue of using woody biomass as a sustainable energy resource remains insufficiently explored. Particularly relevant are areas concerning the regional specifics of biomass use, its impact on local ecosystems, and its potential within the context of forming a balanced energy strategy.

This study aimed to identify the potential for using wood biomass and wood waste in the bioenergy sector of Kyrgyzstan, with an emphasis on their economic feasibility and environmental impact. The objectives of the study were to: analyse the forest resources of the Naryn and Talas regions, identifying forest areas and the prevalence of tree species suitable for biofuel production; estimate the calorific value of different fractions of wood waste; and compare CO_2 emissions from the combustion of wood, coal, and natural gas.

Materials and Methods

The study was conducted in the Kyrgyz Republic across two natural zones: mountainous (Naryn region) and flat (Talas region). These regions were selected due to their differing altitude and climatic conditions, which influence the formation of woody biomass and its energy potential. Field studies were carried out over two growing seasons – 2023 and 2024. This time frame enabled the assessment of wood mass growth dynamics, the availability of forest waste for processing, and the potential for its utilisation in green energy.

The study focused on tree species characteristic of the two selected regions, with particular emphasis on those most commonly used for biofuel production. In mountainous areas, Scots pine (*Pinus sylvestris*) was chosen as the primary species studied. In flat areas, English oak (*Quercus robur*) – which is also widely used as biofuel – was selected as the main species examined. These wood types were chosen based on their prevalence and suitability for energy production within their respective natural environments. The study adhered to ethical standards, including the principles outlined in the Convention on Biological Diversity (1992).

To analyse and compare CO_2 emissions from the combustion of wood waste, coal, and natural gas, the study utilised data obtained from open sources such as scientific publications and environmental reports. Particular emphasis was placed on international experience. For a comparative analysis of the environmental performance of different fuel types, the study also incorporated findings from countries with energy sectors structurally similar to that of Kyrgyzstan. Specifically, it drew on research into the chemical composition and physical properties of natural gas in the Ukrainian energy sector (Chemical composition and..., n.d.), as well as data on coal characteristics within the Ukrainian coal industry (Properties of coals..., n.d.). These sources were selected due to the comparable energy systems of Ukraine and Kyrgyzstan – both of which have a high share of solid fuel in their energy balance and face similar challenges in transitioning to a low-carbon economy. These data were not used as direct regional analogues, but rather as examples of well-established methodological approaches to CO_2 emission analysis that could be adapted to the context of Kyrgyzstan, taking into account national characteristics. Additionally, to estimate carbon dioxide emissions, the study employed the calculation methodology developed by the United Nations Development Programme (2022), which incorporates the national conditions of Uzbekistan. These data facilitated the evaluation of the environmental efficiency of each fuel type. To estimate the forest area in the selected regions, data from the National Statistical Committee of the Kyrgyz Republic (n.d.) were used.

The volume of timber in the study areas was determined as the average value derived from several randomly selected trees. For this purpose, 5-10 typical trees representing the average diameter and height for a given forest zone were identified in each area. Each study area covered 1 hectare, ensuring uniformity in the calculations. This area was applied in both the mountainous and lowland regions, enabling a direct comparison of results under different natural conditions. This methodology ensured the accuracy of the average timber volume calculations and facilitated the interpretation of the research findings under consistent conditions across both study zones. The trunk diameter of each tree was measured using a diameter tape ("Tree Diameter Tape", Forestry Suppliers, Inc., USA, 2010), and tree height was determined using an ultrasonic rangefinder ("Vertex III", Haglöf, Sweden, 2015). The average diameter and height of these trees were then used to calculate volume using the following formula (1):

$$V = g_{1.3} \times H \times F, \tag{1}$$

where: V – volume of the tree (m^3); $g_{1.3}$ – cross-sectional area at breast height (m^2); H – height of the tree (m); F – shape coefficient accounting for trunk form (Forest Measurement and..., n.d.).

The cross-sectional area was calculated using formula (2):

$$g_{1.3} = \frac{\pi d^2}{4}. \tag{2}$$

After calculating the volume for all selected trees, the values were averaged and then divided by the area of the plot to obtain the average wood volume per hectare. The calorific value of wood from different species was determined using laboratory methods with a calorimeter (model IKA C200, Germany, manufactured in 2020). The energy potential was predicted based on the volume of wood and its calorific value, using formula (3):

$$E = V \times Q, \tag{3}$$

where: E – energy potential (GJ); V – volume of wood (m^3); Q – calorific value (GJ/m^3). Subsequently, the study conducted a comparative analysis of the energy potential of three main types of fuel: wood waste (chips, sawdust, bark), coal, and natural gas. To analyse and compare CO_2 emissions from the combustion of wood waste, coal, and natural gas, the study utilised data obtained from open sources, including scientific studies, reports, and environmental publications in industry journals.

The data in the study were processed using statistical methods, including analysis of variance (ANOVA) to assess differences among the three fuels, and the Student's t-test for independent samples to compare the mean calorific values of two fuels. The Shapiro-Wilk test was employed to verify the normality of distribution, and correlation analysis was used to examine relationships between variables. All statistical tests were conducted using SPSS (version 26, IBM, USA). The significance level was set at 0.05, allowing the identification of statistically significant differences between the study groups.

Results

To analyse the potential for using wood biomass and other renewable forest resources in the energy sector, and their impact on sustainable development, various aspects of the issue were considered. Firstly, a general assessment of forest resources was conducted in two selected regions – Naryn and Talas oblasts – taking into account forest area, species composition of woody vegetation, and their potential use for biofuel production (Forest cover of..., n.d.). Based on data from the National Statistical Committee of the Kyrgyz Republic (n.d.), the total forest area in the studied regions was determined.

In Naryn region, where the predominant species is Scots pine (*Pinus sylvestris*), the forest area is approximately 134,400 hectares, of which 92,500 hectares are pine. Scots pine is one of the principal forest-forming species in Kyrgyzstan, widely distributed in mountainous and forested regions, particularly at altitudes between 1,000 and 2,200 metres above sea level. Its wood is used in construction and for the production of woody biomass, which can serve as an energy source. In Talas oblast, where the dominant tree species is English oak (*Quercus robur*), forest cover extends over about 61,100 hectares, of which 27,900 hectares are oak. English oak is also among the main tree species characteristic of the temperate and subtropical zones of Kyrgyzstan (Food and Agriculture Organization, 2019). These forests play an important ecological role in the region, supporting a diverse range of flora and fauna. Oak wood is valued for its strength and durability, and is used in the manufacture of furniture, building materials, and as biomass for energy purposes. These indicators made it possible to estimate the potential volumes of wood biomass available for further processing, thereby opening up opportunities for creating sustainable energy sources from local natural resources.

To refine the potential volume of wood waste suitable for energy use, an analysis of the characteristics of trees selected in each zone was carried out. The volume of wood was determined by measuring the diameters and heights of typical representatives of the dominant species, enabling the calculation of the average wood mass per hectare and its potential energy application. The calculation results presented in Table 1 show the average morphometric indicators of trees and the volume of wood per hectare in the studied regions. These data form the basis for further analysis of the potential volumes of wood waste that can be utilised in bioenergy.

Table 1. Average morphometric characteristics of trees and wood volume per hectare in the studied regions

Region	Wood species	Average diameter at a height of 1.3 m	Average tree height (m)	Form factor	Volume of one deev (m^3)	Approximate number of trees per 1 ha	Total volume of timber per 1 ha (m^3)
Naryn	Pine (*Pinus sylvestris*)	0.28	18	0.5	0.554	800	443.2
Talas	Oak (*Quercus robur*)	0.32	16	0.48	0.617	650	401.05

Source: created by the authors based on open data Chemical composition and physical properties of gas (n.d.), Properties of coals as an object of beneficiation (n.d.), United Nations Development Programme (2022)

The data presented in Table 1 show that in the Naryn region, pine (*Pinus sylvestris*) has an average diameter of 0.28 m and an average height of 18 m, resulting in a total wood volume per hectare of 443.2 m^3. In the Talas region, oak (*Quercus robur*) exhibits an average diameter of 0.32 m and an average height of 16 m, with a total wood volume per hectare of 401.05 m^3. Despite the lower wood volume per hectare in the Talas region, oak demonstrates a higher aspect ratio, which may indicate a more efficient use of wood for energy purposes.

Determining wood volume is essential for assessing the potential of forest resources in the context of bioenergy, as it enables the quantification of available wood residues generated during logging and wood processing. Knowledge of these volumes facilitates the evaluation of the actual performance of biofuel power plants and the estimation of potential thermal and electrical energy output (Bogmans & Li, 2020). Moreover, accounting for tree species characteristics aids in identifying differences in waste generation. Tree species with high wood density tend to have a greater calorific value but may yield a smaller total volume of biomass, whereas less dense species provide larger quantities of wood residues but with slightly lower energy content.

Thus, the analysis not only quantified potential biofuel volumes but also allowed for the development of evidence-based recommendations regarding the rational use of wood waste. Data on the average wood mass per hectare, combined with energy potential calculations, enable the formulation of strategies for the sustainable utilisation of forest resources. This contributes to minimising logging waste and increasing the share of renewable energy sources in the overall energy balance of the region.

To assess the environmental performance of different fuels, the volume of wood was first calculated. Below is an example calculation based on data for Scots pine (*Pinus sylvestris*) in the Naryn region. Typical trees characteristic of the region were selected for the analysis. The average trunk diameter at breast height (1.3 m) was 28 cm (0.28 m), the average tree height was 18 m, and the shape factor, accounting for trunk form, was taken to be 0.5 (Forest Measurement and…, n.d.). The cross-sectional area was calculated using formula (2):

$$g_{1.3} = \frac{\pi d^2}{4} = \frac{3.1416 \times 0.28^2}{4} \approx 0.0616\ m^2.$$

The volume of one tree, calculated using formula (1), is:

$$V = g_{1.3} \times H \times F = 0.0616 \times 18 \times 0.5 \approx 0.554\ m^3.$$

Similarly, calculations were performed for common oak (*Quercus robur*) in the Talas region. The average trunk diameter was 32 cm (0.32 m), the average height was 16 m, and the shape factor was taken as 0.48. The cross-sectional area is:

$$g_{1.3} = \frac{\pi d^2}{4} = \frac{3.1416 \times 0.32^2}{4} \approx 0.0804 \text{ m}^2.$$

Accordingly, the volume of one oak tree is:

$$V = g_{1.3} \times H \times F = 0.0804 \times 16 \times 0.48 \approx 0.0616 \text{ m}^3.$$

These data allowed further estimation of the total volume of wood biomass available for use as a renewable energy source. Based on the calculated wood volume, one of the key indicators of the study was determined: the energy potential. This indicator is crucial as it reflects the efficiency of using wood waste as a renewable energy source. Assessing energy potential enables both the evaluation of the economic feasibility of wood waste utilisation and an understanding of its contribution to sustainable energy development – especially significant in the context of global climate change and the pursuit of sustainable development. The energy potential was calculated not only for the tree species (pine and oak) but also for individual wood fractions used as fuel: chips, sawdust, and bark. Each fraction is characterised by a specific calorific value, which directly affects the total energy yield (Proto *et al.*, 2021). Below is an example calculation of the energy potential using oak bark. For oak, the measured average bark volume in the study area was 0.617 m³, and its calorific value was 9.0 GJ/m³, using formula (3):

$$E = V \times Q = 0.617 \times 9 = 5.55\ GJ.$$

This calculation demonstrates the energy value of oak bark. Similar calculations were performed for the remaining wood fractions and tree species, and the results are presented in Table 2.

Table 2. Energy potential of wood fractions of pine and oak

Wood species	Fraction	Calorific value (GJ/m³)	Volume of wood (m³)	Energy potential (GJ)
Pine (Naryn region)	Wood chips	9.5	0.554	5.26
	Sawdust	10.2	0.554	5.65
	Bark	8.3	0.554	4.61
Oak (Talas region)	Wood chips	10.8	0.617	6.67
	Sawdust	11.5	0.617	7.1
	Bark	9	0.617	5.55

Source: created by the authors based on measured indicators and open data Chemical composition and physical properties of gas (n.d.), Properties of coals as an object of beneficiation (n.d.), United Nations Development Programme (2022)

These data enabled a comparative analysis of the efficiency of using different fractions of wood waste in the energy sector. The analysis of the obtained values reveals several patterns and supports conclusions regarding the feasibility of using wood waste as a renewable energy source. Firstly, it should be noted that the energy potential of various wood fractions varies significantly depending on both tree species and waste type. Among all fractions, wood chips contribute the most to the total energy potential, which can be attributed to their higher density and calorific value compared to other fractions. For pine, this value is 9.5 GJ, whereas for oak it reaches 10.8 GJ, due to the higher density of deciduous wood.

Bark, by contrast, exhibits lower energy potential values than wood chips and sawdust.

For instance, the energy potential of pine bark was 8.3 GJ, and that of oak bark was 9 GJ. This is primarily due to the higher mineral content and moisture in bark, which reduces its calorific value. Nonetheless, the considerable volume of bark generated during logging and wood processing makes it a significant source of biofuel. As for sawdust, its energy potential is also relatively high, albeit slightly lower than that of chips. Specifically, for pine, the value was 10.2 GJ, and for oak, 11.5 GJ. The comparatively high calorific value of sawdust renders it an appealing option for use in compressed biofuels, such as pellets and briquettes. When comparing the energy potential of pine and oak, it is evident that oak waste generally has a higher calorific value, owing to the greater wood density. However, in absolute terms, the total volume of available waste in the Naryn region – where pine predominates – exceeds that in the Talas region – where oak is dominant. This difference in volume may offset the discrepancy in calorific values.

For a more objective comparison of the energy potential of wood fractions with that of coal and natural gas, it is necessary to consider equivalent characteristics for these conventional fuels. Specifically, calorific value, volume, and energy potential must be evaluated, as this enables a more accurate comparative assessment. These indicators are crucial for determining the efficiency of various fuel types in energy systems and for analysing their environmental impact and economic viability, particularly in the context of replacing coal and gas with alternative energy sources such as wood. Table 3 presents data on the key energy characteristics of these two conventional fuel types.

Table 3. Comparative energy potential of coal and natural gas

Fuel type	Calorific value (GJ/kg)	Fuel volume (m^3)	Energy potential (GJ)
Coal (anthracite)	24.5	1	24.5
Coal (bituminous)	20	1	20
Natural gas (methane)	35.8	1	35.8

Source: created by the authors based on open data Chemical composition and physical properties of gas (n.d.), Properties of coals as an object of beneficiation (n.d.), United Nations Development Programme (2022)

A comparative analysis of the energy potential of pine and oak wood fractions with data on the calorific values of coal and natural gas reveals significant differences. For instance, the calorific value of wood fractions ranges from 8.3 GJ/m^3 (for pine bark) to 11.5 GJ/m^3 (for oak sawdust). In contrast, coal has a calorific value in the range of 18-25 GJ/kg, which significantly exceeds that of wood. Natural gas has a calorific value of approximately 38 MJ/m^3, which is also several times higher than that of wood fractions. However, it is important to note that energy potential is only one factor in determining fuel efficiency. Other crucial aspects include emissions of carbon dioxide and other pollutants during combustion. In the case of wood fractions, despite their lower energy potential, their use may result in lower CO_2 emissions compared to coal and natural gas, making them a more environmentally friendly option. The assessment of emissions and their environmental impact plays a critical role in decisions regarding the substitution of traditional fuels with more sustainable and renewable energy sources such as wood.

For a broader analysis of the use of wood biomass and other renewable forest resources in the energy sector – and their implications for sustainable development – it is essential to consider not only the energy potential of wood waste, but also its environmental characteristics. One of the most important factors is the level of CO_2 emissions from the combustion of different fuels, as carbon emissions are a key determinant of energy production's impact on the climate and environment (Brych *et al.*, 2023).

A comparison of carbon dioxide emissions from the combustion of wood waste, coal, and natural gas enables the assessment of the environmental advantages of using wood fuels in place of traditional non-renewable energy sources. This study utilised open-source data to quantify emissions for various fuel types and evaluate their relative environmental impacts. Table 4 presents estimated CO_2 emissions resulting from the combustion of different fuels, including wood waste (chips, bark, and sawdust) in the two study areas, alongside comparative emissions for coal and natural gas. These data support an evaluation of the environmental performance of wood biomass as an alternative energy source when compared to conventional fossil fuels.

Table 4. CO_2 emissions from combustion of different types of fuel

Fuel type	CO_2 emissions (kg/GJ)
Oak chips	90
Oak bark	98
Oak sawdust	80
Pine chips	95
Pine bark	105
Pine sawdust	85
Coal	94
Natural gas	56

Source: created by the authors based on open data Chemical composition and physical properties of gas (n.d.), Properties of coals as an object of beneficiation (n.d.), United Nations Development Programme (2022)

Among wood waste, oak sawdust has the lowest emissions (80 kg CO_2/GJ), which is attributed to its high homogeneity and more efficient combustion, resulting in minimal unburned residue. Oak chips exhibit slightly higher emissions (90 kg CO_2/GJ), explained by their denser structural composition. Oak bark demonstrates the highest emissions (98 kg CO_2/GJ), due to its higher lignin content and mineral impurities, which contribute to increased ash formation and reduced combustion efficiency. A similar pattern is observed for pine. Pine sawdust emits 85 kg CO_2/GJ, which, although higher than that of oak sawdust, remains the lowest among pine-derived fuels. This is due to the higher resin content in coniferous wood, which affects combustion. Pine chips emit 95 kg CO_2/GJ – higher than sawdust, but lower than bark. Pine bark has the highest emissions of all wood waste types (105 kg CO_2/GJ), a result of its high density and significant concentration of carbon-rich compounds.

Nevertheless, when selecting a fuel, not only environmental efficiency but also economic feasibility must be considered. To provide a more comprehensive assessment, a comparative analysis of the cost of obtaining 1 GJ of energy from various fuel types was carried out, and the results are presented in Table 5.

Table 5. Comparison of economic and environmental efficiency of fuel types (per 1 GJ of energy)

Fuel type	Average market price (USD/GJ)	CO_2 emissions	Source of raw materials	Availability in the region	Notes on use
Oak sawdust	5.2	80	Local wood processing companies	High	High calorific value, lowest CO_2 emissions among wood
Pine chips	5.5	95	Logging waste	High	Widely available source, but high CO_2 emissions
Pine bark	4.8	105	By-product	High	Highest CO_2 emissions, need for cleaning
Coal (anthracite)	8.3	94	Import/domestic mines	Limited	High emissions of CO_2 and other toxic compounds
Natural gas (methane)	9.1	54	Imported/ Network	Average/ urbanised area	Lowest CO_2 emissions, but high cost

Source: created by the authors based on open data Chemical composition and physical properties of gas (n.d.), Properties of coals as an object of beneficiation (n.d.), United Nations Development Programme (2022)

The presented analysis allows for the evaluation of both the environmental and economic aspects of using various fuel resources. Among wood waste, oak sawdust has the lowest energy production cost (5.2 USD/GJ), making it the most cost-effective option compared to other wood fractions. It also exhibits the lowest CO_2 emissions (80 kg/GJ), rendering it the most environmentally friendly among the types of wood waste considered. Pine chips, despite a slightly higher cost (5.5 USD/GJ), are readily available and widely accessible, but they are associated with higher CO_2 emissions (95 kg/GJ), which reduces their environmental efficiency. Pine bark, although relatively inexpensive (4.8 USD/GJ), has the highest CO_2 emissions (105 kg/GJ) of all wood waste types analysed. This suggests the necessity of additional emission control measures when using it as a fuel source.

Coal (anthracite) and natural gas have significantly higher energy production costs (8.3 and 9.1 USD/GJ, respectively) compared to wood waste. Moreover, coal is associated with high CO_2 emissions and other toxic pollutants (94 kg/GJ), which diminishes its environmental viability. Natural gas, while having the lowest CO_2 emissions (54 kg/GJ), is comparatively costly, which limits its accessibility – particularly in remote or less urbanised areas. Thus, despite the lower energy density and economic indicators of wood waste compared to coal and natural gas, its use may offer greater environmental benefits and affordability, particularly in regions with abundant raw material availability. The selection of fuel ultimately depends on balancing economic feasibility and environmental impact, highlighting the importance of an integrated approach to energy planning and decision-making (Kalivoshko *et al.*, 2024).

When comparing wood waste and coal, it is noteworthy that coal emits approximately 94 kg CO_2/GJ – similar to the emissions of oak chips (90 kg CO_2/GJ) and pine sawdust (85 kg CO_2/GJ). However, coal is a fossil fuel, and its combustion results not only in CO_2 emissions but also in the release of other harmful compounds, such as sulphur dioxide (SO_2), nitrogen oxides (NO_x), and heavy metals (Golub *et* *al*., 2018). Notably, pine bark produces even higher CO_2 emissions (105 kg/GJ), making it the least environmentally beneficial among all wood waste types. This is attributed to its complex chemical composition, high carbon content, and low combustion efficiency.

Natural gas, by contrast, exhibits the lowest CO_2 emissions of all the fuels considered – 56 kg/GJ. This can be explained by its high methane content and more complete combustion, which results in fewer carbon-based emissions. Even the "cleanest" wood waste, such as oak sawdust (80 kg CO_2/GJ), has emissions that are 42.9% higher than those of natural gas. The most pronounced difference is observed when comparing natural gas (56 kg CO_2/GJ) and pine bark (105 kg CO_2/GJ): pine bark emits 87.5% more CO_2, clearly indicating its low environmental performance.

Thus, wood waste – particularly sawdust – produces lower emissions than coal, though it remains inferior to natural gas in terms of environmental sustainability. The use of bark, especially pine bark, is the least advantageous option among wood fractions due to its high CO_2 emissions and poor combustion efficiency. Although coal's CO_2 emissions are comparable to some wood waste types, its additional pollutant output makes it a less favourable option from an environmental perspective (Lyubchyk *et al*., 2015). Natural gas remains the most environmentally friendly choice, with CO_2 emissions significantly lower than those of all other fuels analysed.

At the same time, sustainable development requires consideration not only of CO_2 emissions but also of fuel availability. In forested regions, wood waste may prove more economically viable despite its higher emissions compared to natural gas. The optimal choice of biofuel should therefore account not only for quantitative emission indicators, but also for combustion characteristics, energy value, and the potential for replacing conventional energy sources – factors that are critical for the transition to renewable energy in the energy sector (National Strategy for..., 2011).

This study provided a detailed response to the research question concerning the environmental and energy efficiency of using wood waste as fuel. An analysis of available wood volumes for energy use revealed that the Naryn and Talas regions possess significant biomass resources suitable for processing. Calculations of the energy potential of different wood waste types confirmed that sawdust and wood chips are the most promising in terms of energy value, whereas bark demonstrated the lowest efficiency and the highest CO_2 emissions.

A comparative analysis of carbon emissions from the combustion of different fuels showed that wood waste is generally a more environmentally friendly option than coal, although it is less favourable than natural gas in terms of CO_2 emissions. At the same time, the significant variation in emissions among different types of wood waste highlights the importance of selecting the optimal fuel type based on specific local conditions and energy requirements (Yerniyazova *et al*., 2024).

Forest ecosystems in the Kyrgyz Republic possess significant potential to support sustainable energy development, particularly through the utilisation of biomass as a renewable energy source. Forests currently cover a substantial portion of the country's territory (approximately 6-7% of the total area), and their resources could become an important component of the national energy strategy in the future. However, the extent to which these ecosystems can contribute to the sustainability of the energy system depends on several factors, including the condition of the forests, the volume of available biomass, and the ecosystem services they provide.

Forest resources can play a vital role in diversifying the country's energy mix if the use of biomass for energy generation is effectively organised. It is generally accepted that biomass derived from forests – such as wood waste and vegetation residues – can meet part of the national energy demand. Estimates of the potential share of this source in the country's energy balance vary, but in the long term, its contribution could reach approximately 10-20% of total energy consumption, depending on the pace of technological advancement and the degree of utilisation of forest resources.

It is important to acknowledge that, at present, forest ecosystems are unable to fully ensure the country's energy security, due to several critical challenges. Firstly, forest resources in certain regions are already under pressure as a result of illegal logging and inadequate forest management practices. Secondly, there is a risk of soil and ecosystem degradation if biomass is harvested for energy without due consideration for the ecological sustainability of forests. Furthermore, the country currently lacks the infrastructure necessary for the efficient collection and processing of biomass into usable energy, which significantly limits its practical application in the energy sector.

The introduction of sustainable biomass utilisation practices can significantly reduce carbon dioxide emissions and lessen dependence on hydrocarbon energy sources. Biomass as an energy source offers a key advantage over fossil fuels – it is considered carbon neutral, meaning that the carbon dioxide released during biomass combustion is offset in the short term by carbon uptake through photosynthesis in vegetation (Lyubchyk *et al.*, 2019).

To utilise biomass effectively, it is essential to develop and implement a range of technologies, such as pyrolysis and gasification, which enable energy production with minimal carbon dioxide emissions. Additionally, the use of biogas derived from organic waste for electricity generation warrants attention. The establishment of a certification system for wood and biomass is also critical to ensure that raw materials used for energy are sourced exclusively from sustainably managed forests (Vasylyshyn *et al.*, 2023). This will help prevent ecosystem overload and preserve ecological balance within biocenoses.

A key component in the successful development of biomass energy is the implementation of incentive and subsidy programmes aimed at building the necessary infrastructure for biomass processing. In this context, financial incentives for private investors and companies developing biomass energy technologies are of great importance. Furthermore, integrating biomass with other renewable energy sources, such as solar and wind installations, can significantly enhance the efficiency and stability of energy production, particularly during periods of low output from other renewables. Equally important is the development of educational initiatives and public awareness campaigns to inform local communities and authorities about the importance of sustainable forest management and the rational use of biomass for energy purposes.

Thus, the forest ecosystems of the Kyrgyz Republic have the potential to become a vital component of the country's sustainable energy strategy. However, realising this potential requires a balanced and well-informed approach to biomass management and utilisation. The deployment of advanced biomass processing technologies, support for sustainable forest practices, and the development of appropriate infrastructure could substantially reduce carbon emissions and enhance the country's energy security in the long term.

The assumption regarding the feasibility of using wood waste as a renewable energy source was partially confirmed during the study. Wood fuels can serve as alternatives to fossil fuels, but their environmental performance varies depending on the specific type of waste, its chemical composition, and combustion properties (Natural coal from..., n.d.). An additional critical factor is the selection of appropriate wood waste sources, which significantly affects the overall efficiency of the energy system. Further detailed studies are needed to evaluate the environmental impacts – particularly CO_2 emissions – of different wood types and to support the development of more sustainable biomass energy solutions.

Discussion

The results obtained in this study provide valuable insights into the potential of using wood waste as a renewable energy source. In the context of efforts to reduce dependence on fossil fuels and advance sustainable energy solutions, the analysis of the efficiency of different biomass types holds significant scientific and practical relevance. The identified differences in calorific value and CO_2 emissions among wood waste fractions enable the optimisation of their application in the energy sector while minimising environmental impact. One of the key findings of the study was the confirmation that wood waste can indeed serve as an alternative to coal, offering lower carbon emissions. However, the variations observed between different types of wood biomass highlight the need for further optimisation of processing and utilisation technologies. In this regard, an important aspect involves comparing the present findings with those of other studies to assess the extent to which the results align with or diverge from existing scientific knowledge.

For a comprehensive evaluation of the significance of the results, it is essential to consider the findings of international researchers, as these offer valuable opportunities for benchmarking against global experience. This not only helps to identify global trends in bioenergy development but also allows for an examination of the different approaches employed in various countries, thereby enhancing understanding of the effectiveness of bioenergy technologies in diverse contexts. Comparing local conditions with international practices facilitates the identification of globally tested solutions that can be adapted and implemented in specific regions, taking into account their unique environmental, economic, and social characteristics. In addition, international research can serve as a source of innovative methods for optimising the processing and utilisation of wood waste, as well as for developing effective models for the sustainable development of the energy sector. The analysis of global experience also helps to identify potential challenges and risks that region may encounter during the implementation of such technologies, thereby enabling the avoidance of common pitfalls and supporting the formulation of strategies for their mitigation. The integration of global best practices, when adapted to regional characteristics, contributes to a more balanced and efficient approach to the utilisation of natural resources, ultimately enhancing environmental and energy sustainability at both local and global levels.

The study by R.G. Khlivitskyi (2023), which examined the volumes of fuelwood harvesting and usage in Ukraine – particularly in the Chuguyevo-Babchansky Forestry branch – is directly related to the present research, as both explore the potential of wood resources for energy production. However, R.G. Khlivitskyi's work is primarily focused on the economic efficiency and potential of fuelwood as a resource for the energy sector, while the current study places greater emphasis on the environmental dimension, particularly the assessment of carbon emissions from various types of wood waste.

Similarly, the article by M. Kiehbadroudinezhad *et al.* (2023) explored the role of biofuels in supporting sustainable microgrids, highlighting their importance in achieving carbon neutrality and promoting a green economy.

This research aligns with the present study in its focus on renewable energy sources to reduce fossil fuel dependency and lower carbon emissions. However, the key distinction lies in its focus on microgrids as a structural solution for integrating biofuels into decentralised energy systems, whereas the present study concentrates on evaluating the efficiency of wood waste as an energy source in a broader, national and environmental context.

The works by N. Khan *et al.* (2021) and C. Lazaridou *et al.* (2021) examined the use of biofuels as a key component in the sustainable transition towards a green economy and carbon neutrality. Specifically, N. Khan *et al.* explore the role of biofuels in achieving a sustainable energy transition, while C. Lazaridou *et al.* focus on forest resources and their recycling within the framework of a circular economy. The present study similarly considers wood waste – particularly sawdust and chips – as more efficient energy sources compared to conventional fuels. The main distinction lies in the broader focus of N. Khan *et al.* work, which encompasses a wide range of recycled materials and does not offer an in-depth analysis of alternative fuel production from wood waste.

Studies by A. Raihan & A. Tuspekova (2022), as well as V.-V. Paunu *et al.* (2021), address the use of renewable energy sources and their environmental impacts, which aligns closely with the objectives of this research. However, those studies are rooted in the specific environmental and economic contexts of Malaysia and the Nordic countries, respectively. In contrast, the current study centres on the utilisation of wood waste in Kyrgyzstan. This comparison underscores the importance of considering contextual factors – such as national energy policies, natural resource availability, and socio-economic conditions – when developing effective strategies for sustainable development and renewable energy use.

The study by B. Kirchsteiger *et al*. (2021) investigated pollutant emissions from domestic wood combustion in Austria, offering a detailed analysis of particulate matter and polycyclic aromatic hydrocarbon (PAH) emission profiles, along with a toxicological risk assessment. This research intersects with the present study in its focus on the environmental aspects of wood waste combustion. However, B. Kirchsteiger *et al*. placed particular emphasis on the health impacts of toxic emissions, an aspect that is also significant within the broader framework of green economy implementation and the assessment of environmental risks to forest ecosystems. Similarly, the health implications of wood waste combustion were examined in the study by H. Timonen *et al.* (2021), further contributing to the understanding of the environmental and public health dimensions of biomass energy use.

The paper by T. Myllyviita *et al.* (2021) highlighted the potential of wood substitution in reducing greenhouse gas emissions, which overlaps with the focus of the current study, as both address the eco-efficiency of wood resource use. However, while the present study concentrates on wood waste as an energy source, T. Myllyviita *et al.* examine broader applications of wood in the context of substituting fossil fuels and lowering carbon emissions across various sectors.

The papers by L.T. Da Silva *et al.* (2021) and O. Thees *et al.* (2023) explored the use of wood fuel in relation to energy potential and the transition to renewable energy sources, aligning closely with the objectives of the current study. Both works emphasise the viability of wood fuel as an alternative energy source that contributes to the reduction of carbon emissions. In particular, O. Thees *et al.* analyse technology development and resource mobilisation in Switzerland, offering a perspective that parallels the investigation into wood waste utilisation in Kyrgyzstan. Meanwhile, the study by L.T. Da Silva *et al.* assesses the energy potential of Eucalyptus sp. wood in Brazil. Although based in a different geographical context, it shares the overarching goal of developing strategic approaches for the sustainable use of wood resources.

The study by M. Adamowicz (2022), along with those by L. Zhang *et al.* (2022) and J. Shao *et al.* (2024), addressed broader issues related to the green economy, sustainable development, and the role of environmental policy in shaping economic sectors. M. Adamowicz examined the influence of the Green Deal and green growth in advancing the Sustainable Development Goals, while L. Zhang *et al.* investigate the interplay between globalisation, the green economy, and environmental challenges. J. Shao *et al.* assess the impact of ecosystem conservation on employment across different industries in Yunnan Province, China. Although these studies address essential themes of sustainable development, they primarily focus on macroeconomic and policy-level dimensions of the green transition. In contrast, the present study offers a more targeted analysis of bioenergy, specifically the use of wood waste in the energy sector of Kyrgyzstan, along with the associated environmental and economic implications. This approach enables the integration of global trends with national-level specifics, contributing to the development of context-sensitive strategies for sustainable energy development. S.M. Shah *et al.* (2021) analyse the influence of "green" human resource management practices on the economic and environmental performance of organisations, highlighting the importance of organisational culture and psychological climate. Although both studies address issues related to sustainable development, their primary focus lies in the institutional and managerial dimensions of the green economy.

A number of studies – by S. Pandey (2022), Y. Sun *et al.* (2022), and A. Olszewski *et al.* (2023) – share a common focus on the processing and utilisation of wood waste, though they approach the subject from different analytical perspectives. A. Besserer *et al.* (2021) explored the cascade use of wood waste, underscoring the value of its multiple applications. M.J. Aliaño-González *et al.* (2022) investigated biomolecules extracted from fruit tree wood waste and their potential uses in the agri-food industry. S. Pandey examined the development of products from low-quality wood waste in Nepal, emphasising the economic and resource importance of such initiatives. Y. Sun *et al.* assess the use of wood biochar for pollutant removal, while A. Olszewski *et al.* proposed a novel method of producing polyurethane composites from wood waste.

While these studies consider wood waste recycling across a variety of sectors – from agri-food to materials science and environmental remediation – the present study focuses on its energy potential. This approach enables an assessment not only of the environmental and economic advantages of wood recycling, but also of its role in advancing sustainable energy and reducing reliance on fossil fuels. The findings of this study regarding the potential of wood waste for energy use are largely consistent with international research, which also supports the adoption of alternative energy sources within the framework of sustainable development. It is noteworthy that most foreign studies affirm the relevance of biomass in replacing traditional fuels and lowering carbon emissions, although the specific approaches and methodologies tend to vary according to local conditions (Green energy and..., n.d.). Unlike studies centred on other national contexts, the current research is distinguished by its focus on the Naryn and Talas regions, with due consideration for their distinct environmental and economic circumstances. Nevertheless, the overarching objective of identifying effective and environmentally friendly energy solutions remains constant.

The comparative analysis of foreign sources revealed both parallels and divergences, highlighting the necessity of further refining methodologies and models that incorporate local conditions and technologies. These findings can inform the development of future research on the use of wood waste, offering new strategies for optimising its application and raising environmental standards across diverse regions.

Conclusions

The results of the analysis conducted in this study confirmed the high energy value of wood waste, supporting its potential as a renewable energy source. Wood chips demonstrated the greatest energy potential (9.5-10.8 GJ), attributable to their high density and calorific value. Sawdust (10.2-11.5 GJ) also showed strong performance, particularly in the context of pellet and briquette production. Bark exhibited the lowest energy potential (8.3-9 GJ), primarily due to its higher content of mineral impurities and moisture.

CO_2 emissions from the combustion of wood waste varied by type. The lowest emissions were recorded for sawdust (80-85 kg CO_2/GJ), followed by chips (90-95 kg CO_2/GJ), while bark displayed the highest emissions (98-105 kg CO_2/GJ). Compared with coal (94 kg CO_2/GJ), wood waste generally demonstrates a lower emission profile – with the exception of pine bark, which exceeds coal in CO_2 emissions. Nevertheless, natural gas remains the most environmentally friendly fuel option, with emissions of just 56 kg CO_2/GJ.

A comparative analysis of relevant scientific publications revealed global trends in the study of wood biomass. In countries with advanced energy infrastructure, research efforts primarily focus on improving combustion technologies and minimising emissions. In contrast, studies conducted in developing regions tend to emphasise the economic feasibility and availability of raw materials. This underscores the importance of adapting international experience to local and regional conditions.

The main limitation of the present study lies in the need for further field testing and a more comprehensive assessment of the environmental and economic impacts associated with the use of wood waste. The findings highlight the necessity for continued research aimed at refining wood biomass utilisation methods, with the dual goals of reducing environmental harm and improving energy production efficiency. Future studies should prioritise the optimisation of biofuel thermal processing, the reduction of emissions from bark combustion, and a detailed economic evaluation of wood fuel integration within the energy sector.

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Conflict of Interest

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Лісові екосистеми в контексті зеленої економіки: потенціал для сталої енергетики

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Анотація. Мета цього дослідження полягала в оцінці потенціалу використання деревної біомаси, включно з деревними відходами, як поновлюваного джерела енергії для енергетичного сектору Киргизстану, а також в аналізі їхньої енергетичної ефективності та екологічних аспектів. Дослідження проводили у двох природних зонах Киргизької Республіки – гірській (Наринська область) і рівнинній (Таласька область). Під час роботи використовували польові дослідження, лабораторні методи і статистичне опрацювання даних. Об'єм деревини на досліджуваних ділянках визначали шляхом вимірювання діаметра і висоти дерев з подальшим розрахунком за встановленими формулами. Для аналізу теплотворної здатності деревини різних порід застосовували калориметричний метод, а для оцінки викидів CO_2 під час спалювання деревних відходів, вугілля та природного газу було використано дані галузевих досліджень. Для порівняння енергетичного потенціалу різних видів палива проведено статистичний аналіз, включно з критерієм Стьюдента та дисперсійним аналізом (ANOVA). Результати дослідження засвідчили, що сосна звичайна та дуб черешчастий є найперспективнішими видами деревини для виробництва біопалива в даних регіонах. Обчислення підтвердили, що тріска та тирса мають найбільшу енергетичну цінність, тоді як кора деревини має найменшу теплотворну здатність. Аналіз викидів CO_2 продемонстрував, що деревні відходи є більш екологічно чистим паливом порівняно з вугіллям, проте поступаються природному газу. Отримані дані підтверджують важливість раціонального використання лісових ресурсів і впровадження деревних відходів у біоенергетику як способу зниження залежності від невідновлюваних джерел енергії та зменшення викидів вуглекислого газу. Дослідження дало змогу з'ясувати, що найперспективнішими видами деревини для біопалива є сосна звичайна та дуб черешчастий. Теплотворна здатність тріски становила 9,5-10,8 ГДж, тирси – 10,2-11,5 ГДж, тоді як кора продемонструвала найменші показники (8,3-9 ГДж). Викиди CO_2 під час спалювання тирси дуба становили 80 кг/ГДж, тріски – 90 кг/ГДж, кори – 98 кг/ГДж, а в сосни ці показники вищі: 85, 95 і 105 кг/ГДж відповідно. Аналіз підтвердив, що деревні відходи екологічно чистіші за вугілля, але поступаються природному газу, що підкреслює їхню значущість для біоенергетики

Ключові слова: деревна біомаса; біоенергетика; деревні відходи; CO_2; енергетичний потенціал; відновлювальні джерела енергії; сталий розвиток

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Features of microclonal propagation of plants of genus *Cercis* L.

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Abstract. Due to the complexity of traditional vegetative propagation of *Cercis* L., it is necessary to use *in vitro* biotechnology to obtain a regenerative aseptic culture with preservation of decorative features. The study aimed to develop methods of microclonal propagation of *Cercis siliquastrum* "Alba" and *Cercis canadensis* L. For this purpose, plant material was collected at different periods of the growing season from plants growing in Kyiv. Statistical and biotechnological methods were used in the study. As a result of the study, two sterilisation modes were tested. The study determined that the efficiency of explant sterilisation and regeneration is influenced by the season of isolation. Using 70% ethyl alcohol and 1% silver nitrate, the sterilisation efficiency of the explants inserted in May was as follows: 20.0 ± 1.8% for *Cercis siliquastrum* "Alba" and 31.3 ± 3.2% for *Cercis canadensis* L. The explants were introduced into *in vitro* culture on hormone-free nutrient medium according to the WPM (Wood Plant Medium) prescription. Aseptic explants were further subcultivation on WPM with 0.4 mg/l BA (N6-Benzyladenine) and 0.3 mg/l 2iP (6-(γ, γ-Dimethylallylamino)purine) and 0.25 mg/l NAA (1-Naphthylacetic acid). The multiplication factor for *in vitro* shoots on WPM with 0.4 mg/l BA was: 9.4 ± 3.5 for *C. canadensis* and 9.7 ± 2.9 for C. siliquastrum "Alba". The use of WPM with 0.3 mg/l 2iP and 0.25 mg/l NAA stimulated active regeneration of in vitro shoots with this multiplication factor: for *C. canadensis* 5.0 ± 1.5 and *C. siliquastrum* "Alba" 6.5 ± 1.5. The research obtained shoots and *in vitro* plants of *Cercis* L. for further use in the landscaping of settlements

Keywords: in vitro plant tissue culture; aseptic explants; in vitro shoots; regeneration; morphogenesis

Introduction

Traditional methods of vegetative propagation of plants of the genus *Cercis* L. are often ineffective due to the complexity of rooting and low regeneration capacity, which limits the mass distribution of these valuable ornamental species in gardening and landscape design, and therefore, the use of microclonal propagation methods is relevant. The study of the peculiarities of microclonal propagation of plants of the genus *Cercis* L. is necessary due to the complexity of traditional vegetative propagation of these ornamental tree species, which limits widespread use in gardening and landscape design. Plants of this genus are valued for high decorative value, due to bright flowering and spectacular leaf colour, but cuttings or propagation by layering is often ineffective due to low rooting percentage and poor regeneration capacity. The use of *in vitro* microclonal propagation methods can solve the problem of preserving and propagating valuable *Cercis* L. genotypes, providing healthy and homogeneous planting material in large quantities. Studying the processes of sterilisation, optimisation of the composition of the culture medium and the regenerative capacity of explants can be used to develop an effective biotechnological scheme for obtaining aseptic cultures, stimulate active shoot formation and ensure successful rooting of regenerated plants.

The provision of high-quality planting material was considered a determining factor in the creation of decorative and sustainable green spaces in urban environments, but traditional methods of propagation of *Cercis* L. plants were ineffective due to the complexity of rooting and the risk of losing donor traits. N. Nimavat & P. Parikh (2024) noted that generative propagation was accompanied by genetic instability and splitting of decorative characteristics of seedlings, which would negatively affect the preservation of valuable plant traits and limit the use of this method for *Cercis* L. L.A. Koldar (2016) noted a low level of rooting of cuttings of *Cercis griffithii* Boss, which ranged from 3.5-6%, which confirmed the problematic use of traditional vegetative propagation for this genus.

In this regard, A. Ram & D. Thomas (2024) substantiated the feasibility of using microclonal propagation as an effective alternative, enabling the mass production of homogeneous and healthy planting material with the preservation of all valuable donor traits in a short time. Similar conclusions were demonstrated by V.I. Voytovskaya *et al.* (2020), describing the peculiarities of the sterilisation of different types of *Rhododendron* L. explants and further propagation *in vitro*. The authors proved that the optimisation of sterilisation regimes is a key step in successful microclonal propagation, as it ensures the production of aseptic cultures with a high level of viability. The researchers emphasised that microclonal propagation methods made it possible to preserve valuable decorative traits inherent in donor plants and to ensure mass production of homogeneous planting material, which is unattainable with generative and traditional vegetative propagation. A. Eisold *et al.* (2024) considered the possibilities of using microclonal propagation to grow ornamental woody plants with valuable decorative properties. The authors noted that traditional methods of propagation are often accompanied by significant difficulties due to low rooting rates and loss of varietal traits, while *in vitro* technology ensured the stability of genetic characteristics and improved many plants in a short time. The researchers concluded that microclonal propagation is feasible and effective as an alternative to traditional methods in ornamental nursery production for growing high-quality planting material.

P. Chmielarz *et al.* (2023) emphasised that the effectiveness of microclonal propagation depended largely on the genotype of donor plants and physiological age, demonstrating the possibility of successfully producing micropropagules even from *Quercus robur* trees up to 800 years old. O. Chornobrov & S. Bilous (2021) and O. Chornobrov *et al.* (2023) demonstrated that *in vitro* technologies ensured the preservation of valuable genotypes and the production of high-quality plant material for nursery purposes.

At the same time, J. Nath *et al.* (2024) emphasised the importance of developing effective explant sterilisation protocols and incorporating the growth characteristics of woody plant tissues to obtain viable aseptic micropropagules with high regeneration capacity. Thus, the analysis of scientific papers confirmed the relevance of microclonal propagation as an effective tool for obtaining high-quality planting material of *Cercis* L. plants suitable for use in horticulture and landscape design.

The study aimed to develop a technology for microclonal propagation of *Cercis siliquastrum* "Alba" and *Cercis canadensis* L.

Materials and Methods

The research was conducted at the Plant Biotechnology Laboratory of the Separated Subdivision of National University of Life and Environmental Sciences of Ukraine "Boyarka Forest Research Station", from May to October 2024. Trees growing on the territory of the Fomin Botanical Garden (*Cercis siliquastrum* "Alba") and on the territory of the nursery of the Department of Forest Restoration and Forest Melioration of the Education and Research Institute of Forestry and Landscape-Park Management aged 25-30 years and 10-15 years, respectively, were used as donor plants. Annual shoots were harvested from the donor plants. To reduce transpiration and loss of turgor, the shoots were placed in a flask of water and refrigerated. Sterilisation and introduction into culture were carried out the day after the shoots were harvested. Cultivation of plant material, sterilisation of laboratory glassware and instruments were performed according to generally accepted methods (Melnychuk *et al.*, 2003; Kushnir & Sarnatska, 2005).

In the laboratory, shoots were cut into cuttings 3-5 cm long. Two sterilisation modes were tested. The general sterilisation process for both modes was washing in soapy water with the addition of a few drops of TWIN-80 surfactant for 20 minutes. A magnetic mixer was used for better washing in soapy water. After that, the cuttings were rinsed with running water for 15 min. Subsequently, the cuttings were filled with sterile distilled water and transferred to a laminar flow box. In the first sterilisation regime, the main sterilising agents were 70% ethyl alcohol and 1% $AgNO_3$. The shoots were immersed in an ethyl alcohol solution for 30-60 s, followed by immersion in a 1% silver nitrate solution for 7-8 min. After sterilisation, they were washed three times in sterile distilled water for 10 min in each portion. After that, the explants were kept on filter paper and cut into 1.0-1.5 cm long pieces. The explants were then planted on WPM (Woody Plant Medium). The results of sterilisation and subcultivation of aseptic viable explants were recorded on day 28 of cultivation.

The second stage of introduction took place in late June and early July. The cuttings were harvested from the same donor trees as for the first introduction. As the shoots were harvested later, they were already semi-lignified, so the second *in vitro* introduction required a different sterilisation regime. The process for the laminar flow box is identical to the first case, with the difference being an increase in the duration of the ethanol soaking and the use of hydrogen peroxide (H_2O_2). After washing the micropropagules in soapy water and rinsing them in running water, they were sterilised in ethyl alcohol for 1-2 min, followed by transfer to a 1% silver nitrate solution for 10 min, after which the cuttings were washed in sterile distilled water for 1 min and then immersed in a 35% hydrogen peroxide solution for 3-4 min. After sterilisation, the explants were washed in sterile distilled water three times for 10 min. The explants were divided into smaller parts and cultured in WPM medium with 1.0 mg/l GA (Gibberellic acid) and 0.1 mg/l TDZ. Explants were counted on day 90 of cultivation. The sterilisation efficiency was defined as the ratio of sterile viable explants to the total number of explants introduced *in vitro* (Melnychuk *et al.*, 2003):

$$K=\frac{A}{L}\cdot 100\%, \qquad (1)$$

where: K – sterilisation efficiency, %; A – number of aseptic viable explants, pcs; L – total number of explants inserted, pcs.

The sterile explants were further subcultured on two variants of WPM medium: 0.4 mg/l BA (variant 1) and 0.3 mg/l 2iP and 0.25 mg/l NAA (variant 2). Transplantation of sterile explants was started on day 32 of cultivation. The plant material was cultivated according to the conventional method in a light room at a temperature of 24 ± 1°C and illumination of 2.0-3.0 klx at a 16-h photoperiod and relative humidity of 70-75%. The hormone-free WPM medium was used as a control. Biotechnological (microclonal propagation) and statistical methods (mean, standard deviation, and one-factor analysis of variance) were used using Microsoft Excel. One-factor analysis of variance (ANOVA) was used to analyse the effect of sterilisation mode on efficacy. The experiments were conducted with four replications.

Results and Discussion

When accounting for the explants introduced into the first sterilisation regime in the *in vitro* culture, the following were obtained: non-viable and non-sterile explants, non-sterile viable and sterile viable explants. The efficiency of the first sterilisation regime was 20 ± 1.8% for *C. siliquastrum* "Alba" and 31.3 ± 3.2% for *C. canadensis*. The study determined that among all explants of *Cercis siliquastrum* "Alba", 24% were infected with biota and were not viable (Fig. 1). Among all explants, 56% were infected, of which 36% did not show signs of growth inhibition (Fig. 2, Fig. 3).

Notably, 4% of explants formed a root 1.52.0 cm long on day 28 of cultivation on hormone-free WPM (Fig. 4).

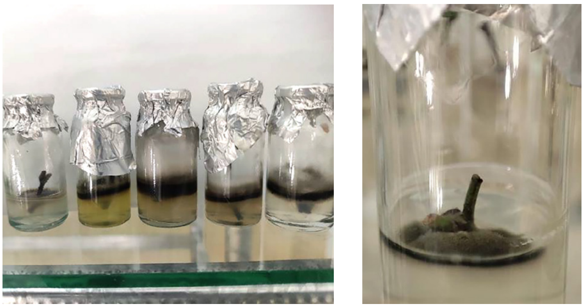


Figure 1. Non-sterile and non-viable explants of *Cercis siliquastrum* "Alba" *in vitro*
Source: authors' photo

Figure 2. Non-viable explants infected with biota
Source: authors' photo

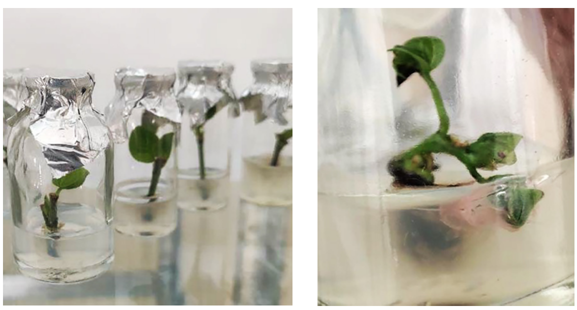


Figure 3. Viable infected explants
Source: authors' photo

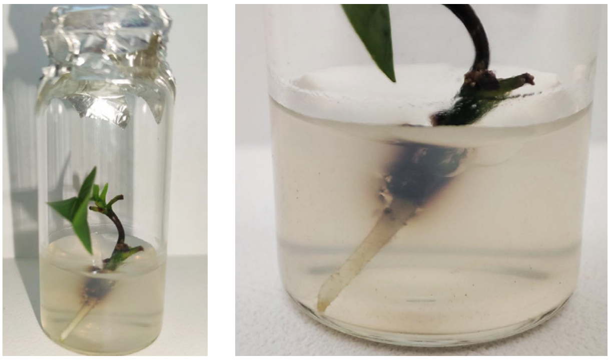


Figure 4. Aseptic explant of *Cercis siliquastrum* "Alba" with root
Source: authors' photo

For *C. canadensis*, the counts revealed that 9.3% of explants were not viable and not sterile; 59.4% were viable but not sterile. A summary of the research findings is shown in Table 1.

Notably, viable explants released secondary metabolites (Fig. 5).

The effectiveness of this sterilisation regime for *C. siliquastrum* "Alba" was 15.8 ± 1.4% (8.8% of them formed shoots, 7.0% showed formation of callus tissue on the sections). Notably, 28.1% of explants were sterile but not viable. For *C. canadensis*, the sterilisation efficiency was 20 ± 3.8% (some explants formed callus tissue) (Fig. 6).

Table 1. Efficiency of sterilisation of explants of *Cercis* L. plants

Species, cultivar	Date of entry	Accounting date	Explants sterilisation mode	Culture medium	Sterilisation efficiency (mean ± standard deviation), %
***Cercis siliquastrum* "Alba"**	21.5.24	21.6.24	soap solution, TWIN-80 (20 min), running water (10 min), 70% C_2H_5OH (30-60 s), 1% $AgNO_3$ (7-8 min), washing with distilled water for 10 min (three times)	hormone-free WPM	20.0 ± 1.8
	28.6.24	2.10.24	soap solution, TWIN-80 (20 min), running water (10 min), 70% C_2H_5OH (1-2 min), 1% $AgNO_3$ (10 min), H_2O (1 min), 35% H_2O_2 (3-4 min), H_2O 10 min (three times)	WPM with 1.0 mg/l GA, 0.1 mg/l TDZ	15.8 ± 1.4
***Cercis canadensis* L.**	21.5.24	21.6.24	soap solution, TWIN-80 (20 min), running water (10 min), 70% C_2H_5OH (30-60 s), 1% $AgNO_3$ (7-8 min), rinsing with distilled water for 10 min (three times)	hormone-free WPM	31.3 ± 3.2
	21.6.24	2.10.24	soap solution, TWIN-80 (20 min), running water (10 min), 70% C_2H_5OH (1-2 min), 1% $AgNO_3$ (10 min), rinsing with distilled water for 1 min, 35% H_2O_2 (3-4 min), H_2O 10 min (three times)	WPM, 1.0 mg/l GA, 0.1 mg/l TDZ	20.0 ± 3.8

Source: compiled by the authors

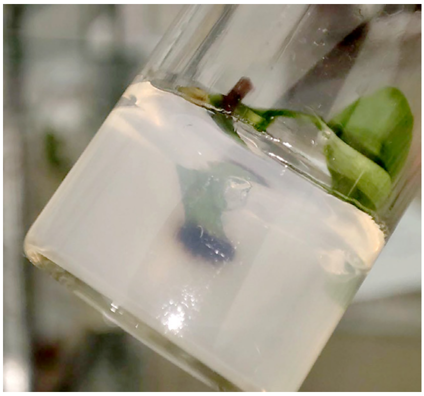


Figure 5. Isolation of secondary metabolites with a sterile explant
Source: authors' photo

Figure 6. Callus tissue on explants of *Cercis canadensis* L.
Source: authors' photo

Among all explants, 25% were not sterile (20% of which were viable), 5% of sterile and non-viable, and the rest were not sterile and non-viable. According to the results of a one-factor analysis of variance (ANOVA), the effect of explant sterilisation on efficiency is statistically significant at the level of 5% ($F > Fcrit$, $P < 0.05$) (Table 2).

Table 2. Results of one-factor analysis of variance for experimental plants

***Cercis siliquastrum* "Alba"**						
Source of variation	***SS***	***df***	***MS***	***F***	***P-value***	***F crit***
Between GROUPS	22.78125	1	22.78125	7.326142	0.035261	5.987378
***Cercis canadensis* L.**						
Between Groups	228.98	1	228.98	7.169815	0.036651	5.987378

Note: *df* – number of degrees of freedom; *MS* – variances; *F* – calculated value of the Fischer criterion; *P-value* – calculated value of the minimum substantiality; *Fcrit* – critical value of the Fischer criterion
Source: compiled by the authors

Among the scientists who were involved in the introduction of *Cercis* plants into *in vitro* culture were L.A. Koldar & M.V. Nebikov (2007). A stepwise sterilisation during the *in vitro* introduction, using sodium hypochlorite (2.5% NaClO), mercury dichloride (0.1% $HgCl_2$) and silver nitrate (1% $AgNO_3$) as sterilising agents, was employed in the study. According to the results, mercuric dichloride showed high sterilisation efficiency in 74-90% of sterile explants, of which 53-78% were viable. This figure decreased significantly after exposure to silver nitrate and amounted to about 20-30% of viable explants, which is quite similar to the results obtained in our study. In contrast to L.A. Koldar & M.V. Nebikov (2007), the current study paid more attention to sterile viable explants and based on this, made conclusions about the effectiveness of sterilisation. After all, sterile non-viable explants have no value in further reproduction. For example, researchers W. Dai *et al.* (2005) used a stepwise sterilisation with two main sterilising agents: 70% ethyl alcohol and 0.6% sodium hypochlorite. The effect of culture medium components on the regeneration ability is shown in Table 3.

Table 3. *In vitro* regeneration ability of shoots of plants of the genus *Cercis* L.

No.	Species, cultivar	Composition of the nutrient medium	Number of shoots per 1 explant, pcs	Length of shoots, cm	Multiplication factor	Characteristics of shoots on the 90th day of cultivation
1	2	3	4	5	6	7
1	*Cercis canadensis* L.	WPM, 0.3 mg/l 2iP, 0.25 mg/l NAA	2.0 ± 1.1	2.5 ± 0.9	5.0 ± 1.5	Callus of granular structure was formed, from light brown to brownish brown in colour; the colour of leaf blades varied from pale yellow to yellow-green, and there were brown areas on the edges of leaf blades.
2		WPM, 0.4 mg/l BA	3.1 ± 2.1	3.0 ± 1.7	9.4 ± 3.5	The callus tissue is white cream to light brown in colour. Explants formed callus tissue with a diameter of 0.5 to 2 cm. The callus was localised both on the surface of the medium and in the explant node. The release of secondary metabolites and the death of the tops of some shoots were observed. The colour of the leaf blades varied from pale yellow with green veins to green yellow.

Table 3, Continued

No.	Species, cultivar	Composition of the nutrient medium	Number of shoots per 1 explant, pcs	Length of shoots, cm	Multiplication factor	Characteristics of shoots on the 90th day of cultivation
1	2	3	4	5	6	7
3	*Cercis siliquastrum* “Alba”	WPM, 0.4 mg/l BA	1.3±0.5	5.3±1.2	9.7±2.9	The callus tissue is formed with a granular structure from light brown to brown with white spots. A small amount of callus was formed. The leaf blades were green or light green in colour, with light brown spots on the edges of some leaves.
4		WPM, 0.3 mg/l 2iP, 0.25 mg/l NAA	1.5±0.5	5.8±1.4	6.5±1.5	Callus tissue is not formed or is formed in rather small quantities, brown in colour. Leaf blades are light green in colour. Secondary metabolites were detected in small amounts.

Source: developed by the authors based on the Nature Reserve Fund of Ukraine (n.d.)

Viable aseptic explants from hormone-free WPM were subcultured on WPM supplemented with 0.3 mg/L 2iP and 0.25 mg/L NAA. A callus was formed from the part of the leaf blade that touched the surface of the medium, which may indicate that this species is capable of reproducing using leaf blades. A callus was also formed on the basal section of the shoots. In both cases, the callus is brownish-brown in colour. Two shoots, 3 and 4 cm long, are formed from the bud. The leaf blades are pale yellow in colour, with brown areas from the edge.

a *b*

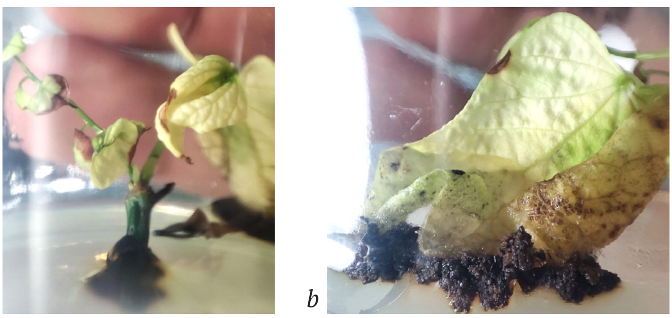
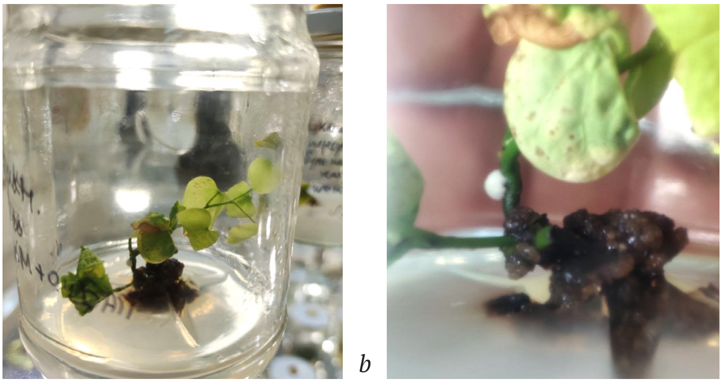


Figure 7. Aseptic shoots of *Cercis canadensis* L.
Note: a – 90th day of cultivation, b – callus tissue formed from the leaf blade
Source: authors’ photo

Subcultivation was performed from hormone-free WPM to WPM supplemented with 0.4 mg/l BA. This explant regenerated callus with significant intensity on the shoots section and in the bud axils of brown and light brown colour, respectively. Also, the formation of white callus tissue in the node area was noted, demonstrated in the images (Fig. 8). As noted by X. Yu *et al.* (2025) in the study on the propagation of *Quercus suber* L., the best substance to reduce the browning of explants was polyvinylpyrrolidone (PVP). The best medium for microclonal propagation was WPM supplemented with trace elements and vitamins per MS.



a *b*

Figure 8. Aseptic culture of *Cercis canadensis* L. (a) and the resulting callus tissue (b)
Source: authors' photo

Notably, this explant intensively secreted secondary metabolites, as well as formed a significant number of shoots. It is possible to assume that an increase in the number of subcultivations of plant material will encourage the development of more shoots on explants (Fig. 9).

Figure 9. Aseptic shoots of *Cercis canadensis* L.
Source: authors' photo

According to S. Yusnita *et al*. (1990), BA had a positive effect on the efficiency of shoots formation from axillary buds. The study noted that with each subsequent subcultivation, the number of newly formed shoots increased significantly. The highest number of shoots was achieved after three subcultivations on a nutrient medium with a concentration of 20 μM (4.5 ppm) BA. Further increases in the number of subcultivations or BA concentration did not give significant results. It can be observed that the shoots formed a significant number of shoots (7-9 pcs), has a productive vegetative part without significant signs of depression, but the tops die off (Fig. 10). This phenomenon is typical for experimental plants in the environment, therefore it is assumed that it is a species-specific feature that persists in *in vitro* culture. J.M. Nielsen *et al.* (1993) claimed that the effect of BA and TDZ on explants of *Miscanthus sinensis* Anderss. In terms of root formation, the proportion of chlorotic shoots and size were the same at identical concentrations of phytohormones. However, as noted by the authors, BA induced a significantly higher number of axillary shoots than TDZ.

Figure 10. Shoots of *Cercis canadensis* L. on WPM with 0.4 mg/l BA
Source: authors' photo

The explant of *C. siliquastrum* "Alba" formed brown and white-brown granular callus tissue, as well as a rather powerful shoot. Furthermore, the vegetative parts were in good condition: the leaf blades were green or light green in colour, but one leaf blade showed pronounced signs of depression and was visually dying. The brownish-brown colour of the culture medium in the basal cut zone should be noted, which may indicate the release of secondary metabolites. Little callus tissue was formed (about 0.7 cm in diameter) (Fig. 11).

Figure 11. Aseptic culture of *Cercis siliquastrum* "Alba"
Source: authors' photo

Oliinyk *et al.* (2017) investigated plants under stress, which occurs when plants are introduced into *in vitro* culture, can synthesise phenolic compounds that are rapidly oxidised, polymerised and cause tissue necrosis. The study recommended the use of gallic acid to reduce tissue auto-intoxication by secondary metabolites. To reduce the negative impact of secondary metabolites, W.A. Mackay *et al.* (1995) recommended the use of activated carbon in the WPM medium at a concentration of 0.1% due to its high adsorption capacity.

Root formation was recorded in 4% of *C. siliquastrum* "Alba" explants on hormone-free WPM on day 28 of cultivation. The shoots was subcultured with the root on WPM with 0.4 mg/l BA. During the examination, it was found that a callus (about 0.7 cm in diameter) was formed in the zone of root regrowth, and no second-order roots were detected. There is a darkening around the roots, which may be secondary metabolites released during the life of the explant. Two shoots 5-7 cm long each were formed (Fig. 12).

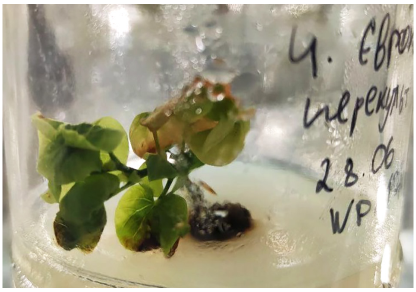


Figure 12. *In vitro* plant *Cercis siliquastrum* "Alba"
Source: authors' photo

C. canadensis shoots cultivated for 135 days on hormone-free WPM medium were 3-5 cm long (explants were infected, visually normal, no necrosis or vitrification was observed, and no regeneration inhibition was recorded) (Fig. 13). The infected shoots of *C. siliquastrum* "Alba" did not show any inhibition in regeneration ability (Fig. 14).

Figure 13. Shoots of *Cercis canadensis* L. at 135 days (hormone-free WPM)
Source: authors' photo

Figure 14. Infected viable shoots of *Cercis siliquastrum* "Alba"
Source: authors' photo

As a result of these studies, aseptic viable shoots and plants of *C. canadensis* and *C. siliquastrum* "Alba" were obtained *in vitro*. Microclonal propagation of plants of the genus *Cercis* was addressed in several studies. When optimising the sterilisation protocol for deciduous plants, the scientists used a stepwise sterilisation using the following substances: ethanol (70%), sodium hypochlorite (5%) and silver nitrate (2%). To improve sterilisation, the authors of the research paper pre-treated the shoots with a fungicide solution: spraying and soaking. The best result in terms of sterilisation efficiency was shown by shoots that were pre-soaked for 24 hours in a fungicide, and then sterilised with ethyl alcohol for 1-2 minutes, followed by keeping in a sodium hypochlorite solution for 10 minutes and finally transferred to a silver nitrate solution for 9-10 minutes. During the propagation of *Sansevieria trifasciata* Prain. K. Panneerselvam *et al.* (2024) used two-stage sterilisation. They note that at the first stage, it was not possible to optimise the sterilisation of leaf explants due to excessive surface infection, therefore, triple sterilisation with ethanol (70%) with different exposure times was utilised. As Ukrainian scientists K. Yevpak & M. Bublyk (2024) determined, the sterilisation efficiency was also affected by the time of *in vitro* introduction. Explants introduced in winter had the highest sterility rate (about 90%), while explants introduced into *in vitro* culture in summer had a sterility rate of only 21%. When *Aronia melanocarpa* (Michx.) Elliott was propagated by D. Abduganiyeva *et al.* (2024) from Uzbekistan, the cuttings were washed in running water to remove solid particles and dust. The scientists also used stepwise sterilisation. The initial explants were sterilised in a solution of domestos (10%) for 30 min, followed by washing 7 times in distilled water, and the shoots were additionally kept in a fungicide solution for 20 min, followed by transferring the explants to a solution of ethanol (70%) for 2 min to remove the residual disinfectant. As a result of this sterilisation protocol, the scientists obtained about 46% of sterile explants.

In particular, L.A. Koldar & M.V. Nebikov (2007) studied the effect of different variants of MS (Murashige & Skoog) nutrient media on the adventitious regeneration of *Cercis* plants (Murashige & Skoog, 1962). The study analysis concluded that the best nutrient medium is a modification of MS with the addition of

2.0 mg/l BA (N^6-Benzyladenine), 0.5 mg/l 3-IAA (3-Indoleacetic acid), and 0.05 mg/l 2, 4-D (2,4-Dichlorophenoxy)acetic acid). The reproduction rate was 3.4 and 11.4 for the first and second passage, respectively. The *in vitro* propagation of *Cercis glabra* Pamp. An emphasis on obtaining polyploid viable plants was conducted by J. Nadler *et al.* (2012). They studied the effect of oryzalin on the induction of polyploidy by different methods of explant treatment.

American scientists led by Wenhao Dai also propagated *Cercis canadensis* L. *in vitro*. They sterilised the explants using a 70% ethanol, followed by transferring the explants to a 0.6% sodium hypochlorite for 15 minutes, containing 3 drops of liquid soap per 100 ml. The shoots were then washed three times in distilled sterile water and blotted dry in sterile paper towels. The actual micropropagation was carried out on 3 nutrient media: MS, DKW (Driver & Kuniyuki Walnut) and WPM (Wood Plant Medium) with the addition of cytokinins, BA and TDZ (Thidiazuron) (McCown & Lloyd, 1981; Driver & Kuniyuki, 1984; Dai *et al.*, 2005). Analysing the works of foreign scientists who were directly involved in the propagation of *Cercis* L. plants, it is possible to conclude that the most common medium was the MS medium variants. For example, when propagating *Cercis yunnanensis* Hu et Cheng, E. Cheong & M.R. Pooler (2003) compared the effect of different growth regulators and explant types on shoot formation and regeneration *in vitro*. The results indicate that the best shoot formation rate was achieved when using MS medium supplemented with 6-BA alone or in combination with TDZ. The multiplication factor was about 3 units. At the same time, when using a hormone-free nutrient medium, the multiplication factor was almost half, namely 1.6 shoots.

In addition to microclonal propagation, *Cercis* was propagated by traditional methods of vegetative propagation. However, R.L. Geneve (1991) noted that stem cuttings of this plant genus are inefficiently propagated, so summer budding is often used. However, according to the author's research, this method is quite expensive due to the fact that the survival rate of budding is less than 50%. Therefore, the study recommended the use of microclonal propagation. Although there are many publications on microclonal propagation of *Cercis* plants, several factors affect the explant *in vitro*, which is why the method was developed individually for each plant.

Thus, the results of the study demonstrate the high potential ability of *Cercis canadensis* and *C. siliquastrum* "Alba" explants for microclonal propagation under *in vitro* cultivation. The dependence of the morphogenetic activity of explants on the number of subcultivations, the type of growth regulators and the composition of the culture medium was established, which is confirmed by both empirical data and literature. These results provide a scientific basis for optimising micropropagation protocols for *Cercis* species, incorporating species characteristics and cultivation conditions.

Conclusions

As a result of the research, a methodology for microclonal propagation of *Cercis canadensis* L., *Cercis siliquastrum* "Alba" plants was developed, aseptic regenerative shoots and plants suitable for further replication and adaptation to environmental conditions were obtained. Using 70% ethanol with an exposure time of 30-60 s and subsequent immersion of explants in a 1% silver nitrate solution for 7-8 min, the sterilisation efficiency was as follows: *C. canadensis* L. 31.3 ± 3.2% and *C. siliquastrum* "Alba" 20.0 ± 1.8%. An effective culture medium for the introduction of explants of the studied plants is hormone-free WPM.

A correlation between the effectiveness of sterilisation and the time of *in vitro* introduction of plant material was revealed. The best time for harvesting cuttings for propagation is May, in the phase of active growth. The efficiency of the sterilisation of explants introduced into the *in vitro* culture in May was almost 1.5 times higher than that of those introduced in late June and early July. The study determined that the mode of sterilisation of shoots of experimental plants significantly influenced the efficiency. To obtain a significant number of shoots and callus tissue of *C. canadensis* and *C. siliquastrum* "Alba", it is advisable to use WPM nutrient medium with the addition of 0.4 mg/l BA. The study determined that the experimental explants formed shoots on hormone-free nutrient medium, but the formation of callus tissue did not occur. As a single phenomenon, root formation was detected in explants of *C. siliquastrum* "Alba" on the 28th day of cultivation on hormone-free WPM.

The release of secondary metabolites in the area around the basal cut of shoots was observed. Since secondary metabolites can adversely affect the micropropagation process, it is recommended to use sorbents, such as activated carbon, which is characterised by high adsorption properties, to reduce this effect. The study determined, employing one-factor analysis of variance (ANOVA), that the sterilisation efficiency of plants of the genus *Cercis* L. is influenced by the sterilisation mode with a statistically significant difference. The regularity that the number of subcultivations of plant material directly affects the shoot formation was revealed.

Further research could address the identification of the biota in non-sterile explants, studying its effect on the organism of plants of the genus *Cercis* L. and investigating the peculiarities of adaptation of plants to environmental conditions.

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Conflict of Interest

None.

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Особливості мікроклонального розмноження рослин роду *Cercis* L.

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Анотація. У зв'язку зі складністю традиційного вегетативного розмноження *Cercis* L., актуальним є застосування біотехнології *in vitro* для отримання регенераційно здатної асептичної культури зі збереженням декоративних ознак. Мета даного дослідження полягала у розроблені методики мікроклонального розмноження рослин *Cercis siliquastrum* 'Alba' та *Cercis canadensis* L. Для цього відібрано рослинний матеріал в різний період вегетації з рослин, що зростали в умовах м. Київ. У роботі використані статистичні та біотехнологічні методи. У результаті проведеного дослідження було апробовано два режими стерилізації. Встановлено, що на ефективність стерилізації та регенерації експлантів впливає сезон ізоляції. За використання 70 % етилового спирту та 1 % нітрату срібла ефективність стерилізації експлантів введених в травні становила: 20,0 ± 1,8 % для *Cercis siliquastrum* 'Alba' та 31,3 ± 3,2 % для *Cercis canadensis* L. Експланти вводили у культуру *in vitro* на безгормональне живильне середовище за прописом WPM (Woody Plant Medium). Асептичні експланти в подальшому субкультивовували на WPM з додаванням 0,4 мг/л BA (N6 –Benzyladenine) та 0,3 мг/л 2iP (6-(γ, γ-Dimethylallylamino)purine) й 0,25 мг/л NAA (1-Naphthylacetic acid). Коефіцієнт розмноження для мікропагонів, культивованих на WPM з 0,4 мг/л BA становив: 9,4 ± 3,5 для *C. canadensis* та 9,7 ± 2,9 для *C. siliquastrum* 'Alba'. Застосування WPM з 0,3 мг/л 2iP і 0,25 мг/л NAA стимулювало активну регенерацію мікропагонів з таким коефіцієнтом розмноження: для *C. canadensis* – 5,0 ± 1,5 та *C. siliquastrum* 'Alba' – 6,5 ± 1,5. Здійснені дослідження дали змогу отримати мікропагони і рослини-регенеранти *Cercis* L. для наступного використання озелененні населених пунктів

Ключові слова: культура тканин рослин *in vitro*; асептичні експланти; мікропагін; регенерація; морфогенез

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Forests as indicators of changes in the geographical landscape

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Abstract. Deforestation and fragmentation of forest ecosystems serve as key indicators of geographical landscape transformation, as they influence regional climate, water balance, and biodiversity, thereby altering ecological stability and natural processes. The study aimed to determine spatiotemporal changes in forest cover between 2016 and 2024, analyse the factors driving these processes, and assess their ecological consequences. To achieve this, satellite imagery, automated land cover classification methods, spatial analysis, and statistical change assessment techniques were employed. The findings revealed significant variations in forest cover dynamics depending on geographical location and natural-anthropogenic factors. The most substantial forest losses were recorded in the Amazon Basin and Central Africa, where forest cover decreased by 9.2% and 8.3%, respectively, due to agricultural expansion, uncontrolled logging, and mineral extraction. In the Balkan region and East Asia, deforestation rates were lower (10.5% and 2.7%); however, increased forest fragmentation and declining bio productivity indicate gradual deterioration of these territories' ecological conditions. In South America, within Mediterranean climate zones, forest cover area decreased by 13%, primarily driven by increased frequency of wildfires and droughts. Analysis of the spatial heterogeneity index demonstrated that forest fragmentation levels rose across all studied regions, reflecting intensified anthropogenic pressure. The results highlighted spatial heterogeneity in forest cover changes and their impact on ecological processes. It was established that forest loss in the studied regions coincides with escalating ecosystem fragmentation, which may alter local climatic conditions, reduce biodiversity, and disrupt water balance. The practical significance of this study lies in the urgent need to develop effective conservation strategies to prevent further degradation of forest landscapes

Keywords: satellite imagery; ecosystem fragmentation; climatic conditions; bio productivity; urbanisation; biodiversity

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Introduction

Forest ecosystems constitute a fundamental component of the biosphere, performing critical functions in maintaining global ecological balance, regulating the carbon cycle, stabilising climatic processes, and preserving biodiversity. However, intensive urbanisation, land-use changes, agricultural expansion, and climate change are driving their degradation. Since 1990, approximately 420 million hectares of forest have been lost, with deforestation accounting for at least 15% of global greenhouse gas emissions. Consequently, studying forests as indicators of geographical landscape changes is essential for understanding the dynamics of natural processes, as forested areas respond to geosystem changes more rapidly than other types of natural complexes. Analysing the spatiotemporal dynamics of forest landscapes enables the identification of transformation trends, assessment of ecological vulnerability, and determination of socio-economic factors influencing environmental change (Adamenko *et al.*, 2023). This, in turn, provides a foundation for developing effective adaptation strategies and sustainable natural resource management.

International organisations play a pivotal role in researching and monitoring changes in forest ecosystems, as well as formulating recommendations for their conservation and restoration. UN programmes, particularly the Forest Landscape Restoration Initiative (n.d.), focus on preserving forested areas and rehabilitating degraded ecosystems (Boiaryn *et al.*, 2023). The Food and Agriculture Organisation (n.d.) actively monitors forest landscape changes, evaluating the impact of climatic factors and anthropogenic activities on forest resources.

Studies on forest landscape changes encompass diverse global regions, revealing both overarching trends and regional specificities. In Albania and the broader Balkan region, as noted by D. Doka & P. Qiriazi (2022), forest landscape transformations were driven by the transition to a market economy. This process triggered active deforestation due to agricultural expansion and illegal logging, though abandoned lands simultaneously experienced natural forest regeneration. Similar dynamics were observed in China, where, according to research by G. Liang & J. Liu (2022), forest cover changes resulted from a combination of climatic factors, erosion processes, and agricultural intensification. In Europe, forest landscapes have also undergone significant alterations, with afforestation contributing to forest defragmentation, though, as established by M. Palmero-Iniesta *et al.* (2020), the nature of these changes depended on regional political and ecological conditions. In South America, the Mediterranean forests of Chile, as concluded by A. Miranda *et al.* (2020), degraded under prolonged droughts, altering the bio productivity of tree stands. Meanwhile, in West Africa, as demonstrated by V. Wingate *et al.* (2023), residual forest patches exhibit high ecological heterogeneity shaped by the interplay of natural processes and anthropogenic activities. Thus, forest ecosystems serve as sensitive indicators of geographical changes, and their dynamics reflect complex interactions between climatic, geomorphological, and socio-economic factors, underscoring the necessity for further comprehensive analysis of these processes.

C. Smith *et al.* (2020) investigated the capacity of secondary forests to compensate for carbon emissions and determined that they can offset less than 10% of emissions caused by primary deforestation. This highlights the limited efficacy of natural forest regeneration in stabilising the global climate. The aspects of spatiotemporal dynamics of landscape changes are examined in the work of I. Hyka *et al.* (2022), who analysed the mechanisms of landscape transformation under the influence of various natural and anthropogenic factors. F. Aimar (2024) proposed a comprehensive approach to reconstructing historical landscape changes based on multi-source analysis. In turn, I. Hyka (2021) investigated urbanisation processes and their impact on landscape structure, applying geographic information system (GIS) analysis and remote sensing methods. Meanwhile, the study by J. Roux *et al*. (2022) focused on the changing societal perception of forests, analysing their evolution from purely resource-based value to objects of spiritual and cultural significance. The authors hypothesised a revival of the sacred meaning of forests, emphasising their role in shaping ecological consciousness. All these scholarly works demonstrate the importance of a comprehensive approach to analysing landscape changes, incorporating historical, ecological, and technological aspects.

Previous studies have not fully elucidated the spatiotemporal patterns of forest cover changes and their impact on landscape processes, leaving the mechanisms of these transformations insufficiently explored. The objective of this study was to analyse forest cover changes in relation to geographical landscape transformation using remote sensing data, GIS methods, and statistical approaches. The study addressed the following tasks: determining the dynamics of forest ecosystem changes, identifying key factors of their transformation, and assessing their impact on the region's ecological stability.

Materials and Methods

The study covered the period from 2016 to 2024, allowing for an assessment of medium-term forest cover change dynamics. The selected period was determined by the availability of high-quality satellite imagery with sufficient spatial and temporal resolution. Data were collected at two-year intervals (2016, 2018, 2020, 2022, 2024) to ensure precise analysis of forest ecosystem transformations.

Five regions were selected for analysis: the Balkans (Albania, Montenegro, Bosnia and Herzegovina), the Amazon Basin (Brazil, Peru, Colombia), East Asia (China, South Korea), South America (Chile, Argentina), and Central Africa (DR Congo, Gabon, Cameroon). The selection of these countries was based on their significant forest cover areas and varying patterns of change. The Balkans and East Asia combine deforestation with forest recovery, the Amazon Basin and Central Africa experience tropical forest loss due to agriculture and logging, and South America suffers from forest degradation due to climate change and wildfires.

To assess forest cover status, satellite imagery from Landsat 8-9 (USA) (U.S. Geological Survey, n.d.a; n.d.b) and Sentinel-2 (Airbus Defence and Space, France/Germany) with a resolution of 10-30 m was used, selected for their regular updates and high accuracy (What you should..., 2024). Pre-processing included atmospheric and geometric correction, aligned with WGS 84, UTM Zone. Accuracy was verified using Global Forest Change (n.d.) (Hansen) data, national geospatial databases, and ground observations.

To evaluate forest cover changes, automated satellite image classification methods were applied, particularly the Maximum Likelihood Classification and Random Forest algorithms. These methods allowed for the identification of major land cover classes: forests, agricultural landscapes, water bodies, and urbanised areas. Additionally, the Normalised Difference Vegetation Index (NDVI) was calculated to assess vegetation cover density and its dynamics (1):

$$NDVI = \frac{NIR-RED}{NIR+RED}, \quad (1)$$

where *NIR* – reflectance in the near-infrared range; *RED* – reflectance in the red range.

Satellite remote sensing data were validated through ground monitoring, conducted using Garmin GPSMAP 64sx receivers (USA) and Leica DISTO D510 laser rangefinders (Switzerland) for precise tree height measurements and coordinate determination. The obtained classification results were integrated into ArcGIS (Esri, USA) and QGIS (open-source software, EU) for spatial analysis of forest landscape changes. The spatial heterogeneity of forest cover was assessed using Shannon's Diversity Index (SHDI), which helped determine the level of forest fragmentation and identify regions with the highest heterogeneity. The SHDI formula is as follows (2):

$$SHDI = -\sum_{i=1}^{n} p_i \ln p_i, \qquad (2)$$

where p_i – the proportion of each landscape class within the total area of the study region; n – the total number of landscape classes in the study region; i – an index denoting a specific landscape class; ln – the natural logarithm used to assess the entropy of distribution. High values of the index indicate significant fragmentation and alterations in forest cover structure. The calculation of this metric allowed for the evaluation of anthropogenic influence and the identification of areas most susceptible to change.

To determine the factors influencing deforestation, correlation analysis (Pearson's and Spearman's coefficients) and regression modelling were conducted. The relationship between deforestation levels and natural as well as socio-economic variables (urbanisation, population density, temperature, precipitation) was assessed using a multiple linear regression model (3):

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta, \qquad (3)$$

where Y – predicted forest cover area; X_1, X_2, X_3 – independent variables (e.g., urbanisation level, mean annual temperature, precipitation amount); β_0 – regression intercept; β_1, β_2, β_3 – regression coefficients, ε – residual term.

Statistical significance was evaluated using Student's t-test and p-values ($p < 0.05$ was considered significant). Model adequacy was verified using the coefficient of determination R^2, which reflected the proportion of explained variance in the dependent variable. The study adhered to international environmental standards, including the Convention on Biological Diversity (1992) and the Convention on International Trade in Endangered Species of Wild Fauna and Flora (1979), which regulate the conservation of forest ecosystems and control their utilisation. All data were obtained from open sources without interference in natural areas or harm to ecosystems.

Results

Spatiotemporal dynamics of forest cover change (2016-2024)

Between 2016 and 2024, all studied regions exhibited a reduction in forest cover area, though the intensity and nature of these changes varied significantly. The most substantial losses were recorded in tropical regions, particularly the Amazon Basin and Central Africa, where the primary drivers were agricultural expansion, uncontrolled logging, and mineral extraction. In these regions, deforestation occurred unevenly: in Amazonia, the most intensive forest loss occurred between 2020 and 2024, coinciding with significant agricultural expansion, whereas in Central Africa, forest degradation exhibited a more stable trend throughout the study period.

In temperate climate regions, particularly the Balkans and East Asia, forest cover dynamics differed from tropical regions. Although the overall forest area declined at a slower rate, satellite analysis indicated increased fragmentation of forest stands and reduced ecosystem bio productivity. In the Balkan region, the primary causes of forest cover loss were urbanisation, climatic shifts, and frequent wildfires (Fuerst-Bjeliš & Glamuzina, 2021). Over 2016-2024, forest area loss here amounted to approximately 9,000 km^2, a considerably lower figure compared to tropical regions, yet indicative of gradual landscape degradation. In Albania, as part of the Balkans, total forest area remained relatively stable, but fragmentation increased, negatively impacting ecosystem connectivity and biodiversity. The main drivers of forest cover reduction were urbanisation, agricultural expansion, and climate change, particularly recurrent droughts leading to declining vegetation bio productivity (Müller & Munroe, 2008). In East Asia, the situation differed: China and South Korea actively implemented afforestation programmes, stabilising forest cover area; however, NDVI analysis revealed a gradual decline in vegetation bio productivity, likely due to shifting temperature regimes and intensified droughts (Yang *et al*., 2021; Gong *et al*., 2021).

Mediterranean forests in South America, particularly in Chile and Argentina, experienced significant losses due to climate change and increased fire frequency (Sharma *et al*., 2019). Between 2016 and 2024, forest cover in this region decreased by 13%, one of the highest rates among studied temperate zones. The primary factors were reduced precipitation and rising temperatures, which promoted forest ecosystem degradation even without anthropogenic influence (Fig. 1). Forest cover change assessment was conducted using a multiple linear regression model (Formula 3).

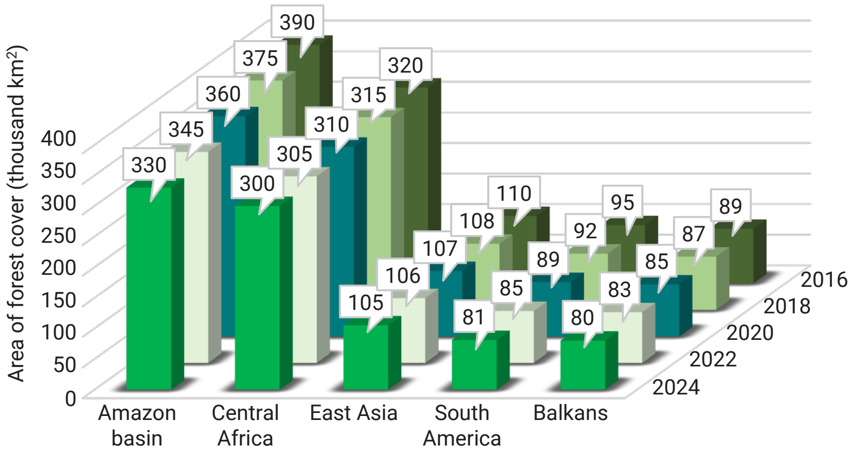

Figure 1. Dynamics of forest cover area changes in the studied regions (2016-2024)
Source: compiled by the author based on U.S. Geological Survey (n.d.a; n.d.b), What you should know about Sentinel-2 climate satellites (2024), J.E. Fa *et al*. (2020)

The obtained results indicate that the rate and scale of forest cover changes are determined by geographical location, climatic conditions, and the level of anthropogenic pressure. In tropical regions, deforestation is most intensive due to uncontrolled exploitation of natural resources, whereas in temperate latitudes, it is more dispersed and depends on the effectiveness of conservation measures. The gradual reduction of forest area in all studied regions confirms their role as key indicators of geographical landscape changes.

The dynamics of NDVI values corroborate the general spatial trends in forest cover changes. In tropical regions, the average NDVI decreased from 0.78 in 2016 to 0.71 in 2024, indicating a reduction in vegetation density. Meanwhile, in the Balkan region and East Asia, although the total forest area remained relatively stable, NDVI also gradually declined, reflecting biomass loss and deteriorating ecosystem health. In Mediterranean-climate South America, this indicator decreased unevenly, with sharp declines during periods of active wildfires, further confirming the role of climatic factors in forest landscape changes (Table 1). NDVI calculations were performed according to formula (1).

Table 1. Dynamics of average NDVI values in the studied regions (2016-2024)

Year	Amazon Basin	Central Africa	Balkans	East Asia	South America (Mediterranean climate)
2016	0.78	0.76	0.65	0.68	0.7
2018	0.76	0.75	0.64	0.67	0.69
2020	0.74	0.74	0.63	0.66	0.67
2022	0.72	0.72	0.62	0.65	0.63
2024	0.71	0.71	0.61	0.64	0.6

Source: compiled by the author

Data analysis reveals that the most intensive NDVI decline was recorded in regions with high anthropogenic impact, particularly the Amazon Basin and Central Africa, where forest degradation is driven by agricultural expansion and uncontrolled logging. In the Balkan region and East Asia, NDVI decline is gradual, indicating relatively stable forest cover, though fragmentation of forest stands and reduced bio productivity signal progressive ecosystem degradation. In Mediterranean-climate South America, the sharp NDVI decline after 2020 points to intensified climatic stressors, manifested in increased wildfire frequency and prolonged droughts. The identified patterns allow not only for an assessment of current trends but also for forecasting further transformation of forest ecosystems under natural and anthropogenic influences. In regions with active conservation programmes, the rate of forest cover loss may be significantly slowed; however, the effectiveness of these measures requires systematic monitoring.

Forest cover changes exhibit significant variations depending on geographical location, climatic conditions, and anthropogenic pressure levels. In tropical regions, the key drivers of deforestation are agricultural expansion, illegal logging, and mineral extraction. In temperate latitudes, dominant processes include forest fragmentation, ecosystem degradation, and the influence of conservation policies. GIS analysis confirms that in the Amazon Basin and Central Africa, the primary causes of forest area reduction are the expansion of agricultural land, soybean production, livestock grazing, and uncontrolled logging. The situation remains particularly critical in the Amazonian tropical forests, where the rate of forest cover loss accelerated sharply after 2020.

In the Balkan region, particularly in Albania, deforestation is localised; however, satellite analysis indicates increasing forest fragmentation and declining ecosystem bio productivity. The main factors here are urbanisation, expansion of agricultural land, and climate change impacts (Doka & Qiriazi, 2022). Unlike other regions, in East Asia (China, South Korea), afforestation policies partially compensate for forest loss, though NDVI analysis confirms gradual biomass reduction due to intensified droughts and temperature regime shifts (Yang *et al.*, 2021). Mediterranean forests in South America have experienced the most significant losses, linked to reduced precipitation, rising temperatures, and frequent wildfires. In Chile and Argentina, the influence of climatic factors has become the primary cause of forest cover reduction, as evidenced by sharp declines in NDVI after 2020 (Temperton *et al.*, 2019).

The obtained results indicate that the main drivers of forest cover change are anthropogenic influence and climate change; however, their impact levels vary significantly across regions. The most critical losses are observed in tropical forests due to intensive land development, whereas in temperate latitudes, the principal challenges remain forest fragmentation, wildfires, and climate change.

The impact of natural and anthropogenic factors on the transformation of forest ecosystems

The interaction of natural and anthropogenic factors influences the dynamics of forest ecosystems across different regions. The impact of these factors is spatially and temporally uneven, necessitating a comprehensive analytical approach. To identify key determinants of forest cover transformation, correlation analysis was performed using Pearson and Spearman coefficients. The results demonstrate a strong negative correlation between urbanisation rates, population density, and forest area, confirming the impact of anthropogenic pressure on forest ecosystem degradation.

A moderately negative correlation was also established between mean annual temperature and forest area, indicating the role of climate change in degradation processes. Rising temperatures lead to more frequent droughts and wildfires, accelerating forest cover loss, particularly in Mediterranean climatic zones. Conversely, precipitation levels show a positive correlation with forest area, underscoring the importance of water balance in maintaining forest ecosystem resilience (Table 2).

Table 2. Correlation coefficients between forest cover changes and natural/anthropogenic factors (2016-2024)

Factor	Correlation coefficient (r)	Significance (p)
Urbanisation rate	-0.78	$p < 0.01$
Population density	-0.74	$p < 0.01$
Mean annual temperature	-0.56	$p < 0.05$
Precipitation amount	0.62	$p < 0.05$

Source: compiled by the author

The findings confirm that anthropogenic factors – particularly urbanisation and population density growth – exert the strongest influence on forest cover change. High rates of rural-to-urban migration and infrastructure expansion contribute to forest area reduction, especially in regions with unstable conservation policies, such as the Balkans and East Asia. Climate change also significantly affects forest ecosystems, though its impact is less pronounced compared to anthropogenic pressure. Increased mean annual temperatures exacerbate droughts and wildfires, particularly in Mediterranean regions of South America and the Balkans. Meanwhile, in tropical regions like Central Africa, high precipitation levels support forest ecosystem preservation despite active timber exploitation.

For quantitative assessment of independent variables' impact on deforestation levels, multiple linear regression modelling was applied (Formula 3). Results showed urbanisation rate ($\beta = -0.74$, $p < 0.01$) to be the primary driver of forest loss, especially in rapidly urbanising regions. The β value for mean annual temperature (-0.37, $p < 0.05$) confirms the negative impact of climate change, though less pronounced than anthropogenic factors. The positive β coefficient for precipitation (0.41, $p < 0.05$) indicates that sufficient moisture levels help maintain forest ecosystem resilience, reducing degradation risks.

Thus, the principal drivers of forest cover loss are urbanisation and population density growth, while climatic factors play a secondary role by amplifying existing degradation trends. The positive influence of precipitation reaffirms the necessity of maintaining hydrological balance as a key stabilisation mechanism for forest ecosystems.

Spatial heterogeneity of forest cover changes and forest fragmentation levels

Spatial heterogeneity of forest cover changes serves as a crucial indicator for assessing the ecological stability of forest ecosystems and regional vulnerability to anthropogenic and natural changes. The Spatial Heterogeneity Index is a key parameter for determining forest fragmentation levels and overall landscape structure transformation. High SHDI values indicate increased forest fragmentation, whereas decreasing values may signify loss of natural diversity or forest cover consolidation (Mina *et al.*, 2021).

Spatial analysis of forest ecosystems using SHDI revealed that in most study regions, an increase in the spatial heterogeneity of forest cover was observed. This indicates a rise in the fragmentation level of forest stands and a shift in their ecological functionality. The highest values were recorded in the Amazon Basin and Central Africa, where the index increased by 17% and 14%, respectively. These changes suggest an active process of disintegration of continuous forest stands into mosaic fragments due to anthropogenic factors, particularly agricultural expansion and uncontrolled deforestation.

In the Balkans, the fragmentation level increased by 8.5%, while in Albania, it rose by 10.9%, reflecting the impact of urbanisation and infrastructure expansion. Although the overall forest cover area in these regions declined at a slower rate, the increase in SHDI indicates intensified processes of internal ecosystem degradation and loss of integrity. In East Asia, the index grew by only 5.3%, which can be attributed to large-scale reforestation programmes; however, the rising fragmentation still points to alterations in forest landscape structure.

The most unstable SHDI values were observed in South America (Mediterranean climate), where, particularly after 2020, the index surged sharply due to extreme weather events, including large-scale wildfires. This confirms that climate change can be as destructive a factor as anthropogenic influence. SHDI calculations were performed using Formula (2). The dynamics of changes in this indicator across the studied regions are presented in Figure 2.

The SHDI data indicate that deforestation processes involve not only quantitative but also qualitative components. Increasing forest fragmentation exacerbates ecological vulnerability, as small, isolated forest patches are less resilient to climate change and anthropogenic pressures. The Amazon Basin and Central Africa exhibit the highest levels of spatial heterogeneity, elevating the risks of biodiversity loss and ecosystem degradation. The Balkans and Albania, despite relatively slower deforestation rates, also show significant fragmentation growth, which may have long-term consequences for regional ecological stability.

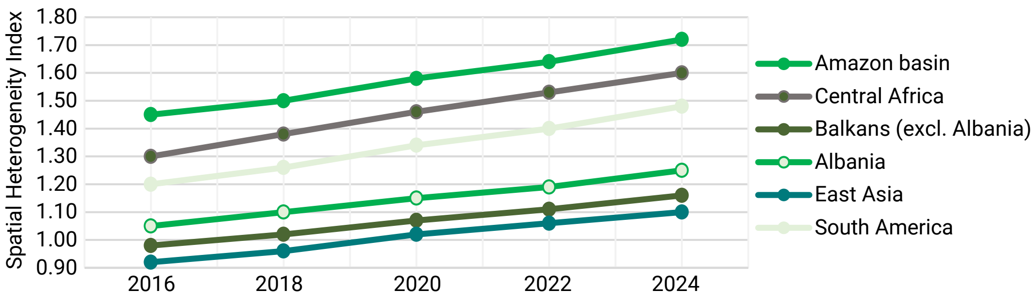

Figure 2. Dynamics of the Spatial Heterogeneity Index in the studied regions (2016-2024)
Source: compiled by the author

The obtained results underscore the need for regionally tailored conservation strategies that consider not only the overall rate of forest cover change but also spatial heterogeneity as a critical factor in assessing ecosystem resilience.

Implications of forest cover changes for regional ecological stability

Changes in forest cover are a critical factor in shaping regional ecological stability, as they influence hydrological processes, biodiversity, and climate regulation. The findings confirm that forest loss and fragmentation lead to complex ecological risks that vary by region. In tropical zones, large-scale deforestation alters local hydrological regimes, reduces groundwater levels, and intensifies erosion. Between 2016 and 2024, forest cover in the Amazon Basin decreased by 9.2%, while in Central Africa, it declined by 8.3%, directly affecting regional and global water balances by reducing precipitation due to diminished plant transpiration. This is particularly hazardous for ecosystems dependent on regular rainfall and may lead to the conversion of humid tropical forests into degraded savannas (Daskalova *et al.*, 2020; Takam Tiamgne *et al.*, 2022).

In temperate latitudes, particularly in the Balkans and East Asia, the primary consequences of forest cover changes include increased flood risks, soil instability, and rising annual temperatures. Forest cover losses during the study period reached 10.5% in the Balkans (excluding Albania) and 11.2% in Albania, impairing the water-regulating function of forest ecosystems and reducing soil moisture retention while increasing flood risks during heavy rainfall (Ferrara *et al.*, 2017). In East Asia, forest cover decreased by 2.7%, a relatively low figure; however, satellite analysis confirmed gradual ecosystem degradation due to forest fragmentation and declining bio productivity, even in regions with active reforestation programs, such as China and South Korea (Shi *et al.*, 2024).

A particularly pronounced impact of forest cover changes is observed in Mediterranean climate regions, notably in South America. Here, the main risks are associated with increased wildfire frequency and reduced soil moisture reserves (Agnoletti *et al.*, 2022). The study data confirm that between 2016 and 2024, the average forest area in Chile and Argentina decreased by 13%, correlating with rising air temperatures and declining precipitation. Forest loss heightens the risks of desertification and soil degradation, which may, in the long term, reduce agricultural productivity and exacerbate water scarcity (Bax & Francesconi, 2018; Santos *et al.*, 2019).

Another critical ecological consequence of forest cover changes is biodiversity decline. In tropical regions, deforestation directly reduces habitats for numerous species, threatening their extinction (Abdullah *et al.*, 2019). In Central Africa, forest loss leads to the disappearance of unique ecosystems that host many endemic species. In temperate climates, forest fragmentation creates isolated populations, reducing genetic diversity and increasing extinction risks due to climate change or disease (Svensson *et al.*, 2019).

The analysis of the obtained data in the context of ecological stability confirms the importance of forests as natural regulators of climatic processes and stabilisers of landscape structures. All studied regions demonstrate a clear correlation between forest cover levels and resilience to climatic and hydrological changes. In regions where forest cover is rapidly declining, ecological instability risks increase, as evidenced by the correlation between forest dynamics and the rising frequency of extreme weather events.

Discussion

The obtained results allow for an assessment of the patterns of forest cover change across various regions and the identification of key factors influencing these processes. A comparison with other studies provides deeper insights into the ecological and socio-economic consequences of deforestation and potential strategies for its mitigation.

The analysis revealed the most significant forest losses in the Amazon Basin and Central Africa, where deforestation is driven by agricultural expansion, illegal logging, and mineral extraction. In the Balkan region and East Asia, increased forest fragmentation and declining bio productivity were observed, indicating progressive ecosystem degradation. Similar patterns were identified by B. Fuerst Bjeliš & N. Glamuzina (2021), who analysed historical forest cover changes in the Balkans, highlighting the long-term interaction between natural processes and socio-economic transformations shaping forest landscape distribution. The work of D. Müller & D. Munroe (2008) also demonstrates the substantial impact of post-socialist changes in Albania, which led to both forest degradation and regeneration on abandoned agricultural lands, partially aligning with the trends identified in this study.

In East Asia, deforestation is largely attributed to rapid urbanisation and land-use change (Kerimkhulle *et al.*, 2023). As noted in the study by C. Yang *et al.* (2021), the rapid expansion of cities in the Pearl River Delta has caused significant forest cover loss, consistent with the findings on forest ecosystem dynamics in China and South Korea. Meanwhile, research by J. Gong *et al.* (2021) confirms that effective spatial planning and optimisation of forest distribution can contribute to maintaining ecological balance in mountainous regions, a crucial factor in mitigating the adverse effects of deforestation.

In tropical regions, ecosystems are significantly affected not only by anthropogenic factors but also by climatic changes (Horbachova *et al.*, 2025). As demonstrated in the study by R. Sharma *et al.* (2019), land-use transformation in tropical forests directly impacts ecosystem services, including water balance, climate regulation, and biodiversity. These conclusions align with the obtained results, which highlight the negative effects of forest cover degradation in the Amazon Basin and Central Africa, where reduced forest area correlates with increased risks to local hydrology and ecosystem stability. The importance of indigenous lands in preserving intact forest landscapes is further supported by the research of J. Fa *et al.* (2020), emphasising the need for an integrated forest management approach that considers both ecological and social aspects of sustainable development.

The findings indicate that forest cover changes are largely determined by a combination of natural factors, such as climatic fluctuations and soil degradation, and socio-economic drivers, including urbanisation, agricultural expansion, and natural resource management policies. Similar trends were observed in the study by S. Mansourian *et al*. (2020), which examined the integration of forest landscape restoration approaches and found that restoration effectiveness heavily depends on the alignment of ecological and economic strategies. Conversely, research by V. Temperton *et al*. (2019) confirmed that successful forest ecosystem restoration is only achievable when considering broader ecological contexts, consistent with the observed regional differences in deforestation and recovery trends. In turn, M. Mina *et al*. (2021) demonstrated that forest landscape management should be based on network analysis of ecological connectivity, aligning with the conclusions on the impact of forest fragmentation on stability in the studied regions.

In the context of ecosystem changes and biodiversity, the study by G. Daskalova *et al*. (2020) demonstrated that landscape-level forest loss acts as a catalyst for shifts in species population structure, corroborating the findings on ecological risks, particularly in regions with high fragmentation. Meanwhile, research by X. Takam Tiamgne *et al*. (2022) confirmed that in areas with intensive natural resource extraction, deforestation becomes irreversible, as also observed in Central Africa and the Amazon Basin. Additionally, the results of C. Ferrara *et al*. (2017) underscore the importance of socio-economic context in forest conservation, corresponding to the identified trends linking forest cover change rates to anthropogenic pressure levels and conservation management policies.

The findings confirm that forest cover degradation significantly impacts ecosystem processes, including water balance, biodiversity, and climate regulation. Similar trends were identified by X. Shi *et al*. (2024), who demonstrated that landscape changes directly affect water resource quality, particularly in regions with high deforestation rates. This aligns with the results indicating a correlation between reduced forest cover and intensified erosion processes in tropical regions, threatening soil water retention capacity. The study by M. Agnoletti *et al*. (2022) analysed the influence of cultural and social factors on forest ecosystem dynamics, emphasising that historical land-use changes leave long-lasting imprints on landscape structure. This aligns with the findings obtained for the Balkan region, where, following the socio-economic transformations of recent decades, both natural forest regeneration and ecosystem fragmentation have been observed. F. Santos *et al*. (2019) employed geographically weighted random forests to assess deforestation determinants in tropical regions of the Amazon, confirming that local natural factors play no less significant a role than socio-economic processes. These results correlate with observations conducted in Central Africa, where the topographic features of the region influence the rate and scale of forest cover change.

The analysis of spatiotemporal changes in forest cover and their ecological consequences confirms general trends regarding the impact of natural and anthropogenic factors on the degradation of forest ecosystems (Fedoniuk *et al*., 2024; Porokhniava *et al*., 2024). Research conducted by V. Bax & W. Francesconi (2018) demonstrated that in the tropical Andes, the natural susceptibility to deforestation – particularly due to steep slopes and vulnerable soils – significantly amplifies anthropogenic influence. Similar processes are observed in Central Africa and the Amazon Basin, where topographic and climatic factors determine the rate of forest degradation. The study by H.Abdullah *et al*. (2019) revealed that deforestation is most pronounced in regions with rapid urban infrastructure expansion, which corresponds to observations in the Balkan region and

East Asia, where urbanisation is one of the key drivers of forest cover loss. J. Svensson *et al*. (2019) established that the decline of natural boreal forests poses significant obstacles to the formation of "green infrastructure" necessary for maintaining ecological stability. Comparable trends are observed in Mediterranean-climate regions, where increased forest fragmentation, frequent wildfires, and reduced precipitation complicate natural forest regeneration.

The results of this study confirm the substantial impact of climate change and anthropogenic factors on forest ecosystems, which is consistent with previous scientific works. Research by A. Kerebel *et al*. (2019) demonstrated that modelling landscape changes using Bayesian networks allows for the assessment of spatial heterogeneity in forest degradation, correlating with the obtained results on forest cover fragmentation in the Balkan region and Central Africa. J. Huang *et al*. (2021) determined that shifts in climatic conditions contribute to changes in forest species composition, which is also observed in Mediterranean-climate regions, where rising temperatures and declining precipitation affect ecosystem bio productivity. The study by S. Wilson *et al*. (2017) emphasised that changes in ecosystem services associated with forest area reduction may lead to significant socio-economic shifts, resonating with the identified impact of urbanisation on forest decline in East Asia.

Furthermore, the work of A. Syphard *et al*. (2024) established that future fire patterns under climate change can be predicted based on geographical factors, corresponding to the identified relationship between fire intensity and forest cover reduction in South America. Research by C. Hunsberger *et al*. (2017) confirmed that global forest conservation initiatives may conflict with local land-use practices, aligning with the obtained data on the substantial influence of agricultural expansion on deforestation in tropical regions. The analysis by G. Simon & C. Peterson (2019) demonstrated that historical forest management policy changes have determined resource utilisation levels and degradation scales, correlating with the observed differences in forest cover dynamics between regions with active reforestation programmes and those lacking conservation measures.

The results confirm that forest cover reduction has varying ecological and socio-economic consequences depending on the region. In the tropics, agricultural expansion and logging dominate, whereas in temperate latitudes, urbanisation and climate change prevail. Comparisons with other studies highlight the necessity of integrated forest resource management to maintain ecosystem stability.

Conclusions

The study confirmed that forest cover changes serve as critical indicators of geographical landscape transformation, with their dynamics largely determined by a combination of natural and anthropogenic factors. An analysis of data from 2016-2024 demonstrated that the most intensive forest area reduction occurred in tropical regions, particularly the Amazon Basin and Central Africa, where losses reached 9.2% and 8.3%, respectively. The primary determinants of these changes include agricultural land expansion, illegal logging, and mineral extraction.

In temperate climate regions, such as the Balkans and East Asia, forest area declined less intensively; however, satellite analysis confirmed increased forest fragmentation and reduced ecosystem bio productivity. In the Balkan region, forest cover losses amounted to 10.5% (excluding Albania) and 11.2% (Albania), accompanied by an increase in spatial heterogeneity of 8.5% and 10.9%, respectively. In East Asia, forest area decreased by 2.7%, indicating relatively stable processes, though forest fragmentation combined with urbanisation pressure remains a significant issue.

Mediterranean forests in South America proved among the most vulnerable to climate change. During the study period, forest cover losses in Chile and Argentina reached 13%, attributed to frequent wildfires, droughts, and declining precipitation. NDVI analysis showed that the average forest bio productivity level in this region decreased from 0.7 in 2016 to 0.6 in 2024, indicating substantial vegetation degradation.

Correlation analysis confirmed that urbanisation rates and population density growth are the primary factors of forest cover loss ($r = -0.78$ and $r = -0.74$, respectively, $p < 0.01$), whereas mean annual temperature has a less pronounced yet still negative impact ($r = -0.56$, $p < 0.05$). A positive correlation with precipitation levels ($r = 0.62$, $p < 0.05$) underscores the importance of hydrological balance in maintaining forest ecosystem resilience.

The obtained results hold significant implications for formulating forest conservation and restoration strategies across different climatic zones. In tropical regions, stricter environmental protection measures and enhanced control of illegal logging are imperative, whereas in temperate latitudes, the focus should be on minimising forest fragmentation. Particular attention must be paid to Mediterranean-climate regions, where adaptive measures to combat climate change – including fire prevention and water resource management – are essential.

The study is constrained by the spatial resolution of satellite data, which may affect the assessment of small-scale forest cover changes. Additionally, only primary natural and socio-economic factors were considered, without a detailed analysis of local land-use specificities. To enhance the accuracy of future research, the integration of high-precision climate models, granular socio-economic indicators, and ground-based measurements for satellite data validation is recommended.

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Conflict of Interest

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Ліси як індикатори змін географічного ландшафту

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Анотація. Знеліснення та фрагментація лісових екосистем є ключовими індикаторами трансформації географічних ландшафтів, оскільки вони впливають на регіональний клімат, водний баланс та біорізноманіття, змінюючи таким чином екологічну стабільність та природні процеси. Метою дослідження було визначити просторово-часові зміни лісового покриву в період з 2016 по 2024 роки, проаналізувати фактори, що зумовлюють ці процеси, та оцінити їхні екологічні наслідки. Для цього були використані супутникові знімки, автоматизовані методи класифікації рослинного покриву, просторовий аналіз та методи статистичної оцінки змін. Результати дослідження виявили значні відмінності в динаміці лісового покриву залежно від географічного розташування та природно-антропогенних чинників. Найсуттєвіші втрати лісів були зафіксовані в басейні Амазонки та Центральній Африці, де лісистість зменшилася на 9,2 % та 8,3 % відповідно через сільськогосподарську експансію, неконтрольовані рубки та видобуток корисних копалин. У Балканському регіоні та Східній Азії темпи вирубки лісів були нижчими (10,5 % і 2,7 %), однак збільшення фрагментації лісів і зниження біопродуктивності свідчать про поступове погіршення екологічного стану цих територій. У Південній Америці, в межах середземноморського кліматичного поясу, площа лісового покриву скоротилася на 13 %, насамперед через збільшення частоти лісових пожеж та посух. Аналіз індексу просторової неоднорідності показав, що рівень фрагментації лісів зріс у всіх досліджуваних регіонах, що відображає посилення антропогенного тиску. Отримані результати висвітлили просторову неоднорідність змін лісового покриву та їх вплив на екологічні процеси. Встановлено, що втрата лісів у досліджуваних регіонах збігається з ескалацією фрагментації екосистем, що може змінювати місцеві кліматичні умови, зменшувати біорізноманіття та порушувати водний баланс. Практичне значення дослідження полягає в нагальній потребі розробки ефективних природоохоронних стратегій для запобігання подальшій деградації лісових ландшафтів

Ключові слова: супутникові знімки; фрагментація екосистем; кліматичні умови; біопродуктивність; урбанізація; біорізноманіття

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The impact of forest fires on ecosystem

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Abstract. Fires cause significant changes to forest structure, disrupt ecological connections, and affect recovery processes. This study aimed to assess the extent of damage to tree stands and compare the resistance of coniferous and deciduous species to fire. The impact of these phenomena on various tree species and the functioning of forest ecosystems in northeastern Ukraine, which experienced large-scale fires between 2022 and 2024, was analysed. The analysis included an

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examination of damage to the bark, trunk, root system, and tree crowns, as well as an assessment of natural succession processes. Coniferous species, such as Pinus sylvestris L., were found to be the most vulnerable: approximately 60% of trees were either completely destroyed or severely damaged, and 70% of root systems lost their ability to recover. The crowns were destroyed in 80% of cases, leading to a reduction in tree stand density. In contrast, deciduous species such as oak and maple demonstrated greater fire resistance, with only 20-30% of trees sustaining severe damage, most of which successfully regenerated through regrowth. Mosses and lichens, which play a crucial role in soil stabilisation, were among the most affected, with their populations declining by more than 40%. This disruption in natural succession processes negatively impacted forest regeneration. Fires also increased forest fragmentation, underscoring the importance of creating ecological corridors and enhancing connectivity between forested areas to facilitate natural recovery. It is recommended to develop adaptive forest management strategies that consider the increasing frequency of fires, driven by both natural factors (such as climate change) and anthropogenic influences. The spread of fires caused by military activities is particularly relevant to the northeastern region of Ukraine. Determining tactical and strategic approaches for managing such areas requires consideration not only of the specific dynamics and patterns governing forest ecosystems but also of security-related factors. Military actions act as an additional powerful force driving environmental transformation and pollution. Addressing these challenges should form an integral part of programme documents concerning the post-war restoration of Ukraine's natural complexes

Keywords: biodiversity; ecological fragmentation; succession processes; natural regeneration; remote sensing; adaptive forest management

Introduction

Fires are among the most powerful environmental factors, exerting a diverse impact on ecosystems and posing one of the most serious threats to forested areas in Ukraine. This risk is particularly pronounced in the context of global climate change, which has led to an increase in the frequency of droughts and the duration of hot periods. In particular, fires disrupt the integrity of forest landscapes and their ecological connections (Jones *et al.*, 2021; Slattery & Fenner, 2021). Additionally, fires exacerbate the degradation of forest ecosystems by destroying root systems and tree crowns, as highlighted in the studies of F. Niccoli *et al.* (2023). However, the extent and nature of both the direct and indirect impacts of fires are also determined by the intrinsic properties of forest ecosystems, including the species composition of different vegetation layers, particularly the living aboveground cover, which plays a crucial role in soil stabilisation and moisture retention (Hu *et al.,* 2020; Thielen *et al.*, 2021; Kakeh *et al.*, 2021). M. García-Carmona *et al.* (2021) demonstrate that mosses and lichens, which are significantly affected by fires, recover very slowly, and their loss is often accompanied by increased soil degradation. The changes induced by fires also influence succession dynamics and natural forest regeneration (Vanderhoof *et al.*, 2020; Hishe *et al.*, 2021).

Since the onset of the large-scale invasion by the Russian Federation, fires have affected vast areas of Ukraine, including extensive forested regions. According to the State Emergency Service of Ukraine, artillery and rocket attacks have triggered numerous forest fires, complicated firefighting efforts and causing large-scale environmental damage (Over the past 24 hours..., 2024). Under these conditions, fires have not only become more frequent but also significantly more hazardous, as military operations have impeded rescue services' access to affected areas and reduced their ability to respond effectively (Sumy region..., 2024).

Due to its border location with the aggressor country, fires have become widespread across northeastern Ukraine. Existing literature already documents fires in the Desniansko-Starohutskyi National Nature Park (NNP), which covers an area of 16,215.1 hectares, including 7,231.5 hectares of forested land, primarily represented by the Starohutskyi forest massif. The vascular plant flora of the Desniansko-Starohutskyi NNP comprises 880 species, making it the most floristically diverse among the national parks and reserves of Polissya. Within its territory, 35 plant species are listed in the Red Book of Ukraine, alongside 49 regionally rare species. The park's fauna also exhibits a high degree of biodiversity and significant ecological value. A substantial number of vertebrate species recorded in the Desniansko-Starohutskyi NNP are included in both national and international Red Lists and conservation agreements. Specifically, the protected species include: Red Book of Ukraine – 39 species; Red List of the International Union for Conservation of Nature (IUCN) – 34 species; European Red List – 11 species; Convention on International Trade in Endangered Species of Wild Fauna and Flora (1973) – 39 species; Convention on the Conservation of Migratory Species of Wild Animals (1979) – 55 species; Convention on the Conservation of European Wildlife and Natural Habitats (Appendix II, 1979) – 170 species (Periodic review for..., 2020).

Among the fires caused by the aggressor country, the largest occurred in May 2023 (Shaforost *et al*., 2024). It raged for more than a week, with no possibility of extinguishment due to the danger posed by its proximity to the Russian Federation's border. As a result of this fire, 32 forest blocks within the Desniansko-Starohutskyi National Nature Park were affected. This represents one-fifth of the land covered with forest vegetation and one-third of the recreational zone. The area of forest phytocenoses damaged by the fire primarily consisted of *Pinus sylvestris* L. stands over 60 years old, growing in conditions of fresh pine-oak (B2DS) and moist pine-oak (B3DS) forests. The herbaceous and shrub layer, including *Vaccinium myrtillus* L. and *Vaccinium vitis-idaea* L., also suffered damage. Populations of plant species representing rare phytodiversity, particularly those protected at the national or regional levels, were significantly affected. These include *Huperzia selago* (L.) Bernh. ex Schrank et Mart., *Lycopodium annotinum* L., *Carex brunnescens* (Pers.) Poir., *Salix starkeana* Willd., *Dactylorhiza fuchsii* (Druce) Soó, *Epipactis helleborine* (L.) Crantz, *Platanthera bifolia* (L.) Rich., *Dactylorhiza incarnata* (L.) Soó, and *Salix myrsinifolia Salisb*. (Andrienko, 2006). The fauna of the national nature park was also significantly impacted.

The issue of fire spread and its impact on the natural complexes of northeastern Ukraine, against the backdrop of the large-scale invasion, was also addressed in the project Assessing the Environmental Consequences of War for Communities. This study focused on the Khotyn and Velykopysariv communities in the Sumy region, both of which are located near the state border with the Russian Federation. According to the project's findings, which included satellite monitoring using archival data from the NASA FIRMS service (covering the period from 24 February 2022 to 15 August 2023), fires were recorded over an area of 196.13 hectares in the Khotyn community and 210.36 hectares in Velykopysariv. Additionally, a fire covering 9.5 hectares was detected in the forest massif of the Hetman National Nature Park within the Velykopysariv territorial community (Assessing the environmental…, 2023).

These findings indicate that, at present, the impact of fires on Ukraine's environment is increasing significantly, particularly in regions where natural complexes have been affected by the war. Consequently, further research is required on how forest ecosystems respond to pyrogenic factors. Such studies should not only contribute to understanding the ecological relationships characteristic of modern forest ecosystems but also form a scientific basis for developing strategic and tactical approaches to the post-war restoration of Ukraine's natural complexes.

Thus, the aim of this study was to examine the impact of pyrogenic factors on the dominant forest-forming species and forest phytocenoses of northeastern Ukraine, with a focus on identifying priority measures for mitigating the consequences of fires and reducing their negative impact.

Materials and Methods

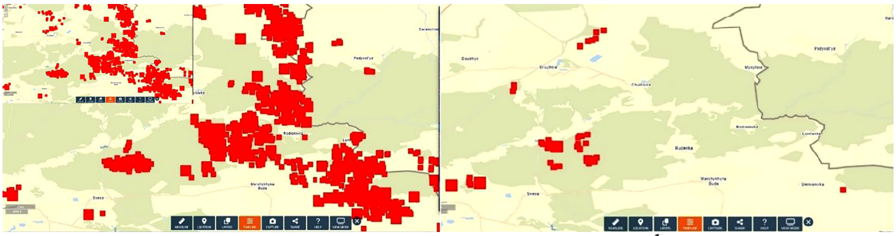
To assess the impact of forest fires on biodiversity and ecosystem functioning, a comprehensive study was conducted in northeastern Ukraine, specifically within the Sumy region and the adjacent areas of the Chernihiv and Poltava regions, covering the period from 2022 to 2024. The analysis of fire effects on forest stand structure began with an examination of the responses of coniferous and deciduous trees to fire. The primary focus of the study was on key tree species, including Scots pine (*Pinus sylvestris* L.), common oak (*Quercus robur* L.), and sycamore maple (*Acer platanoides* L.). An inventory of trees was conducted to estimate the number of surviving and dead specimens. During field studies, damage to the bark, trunk, root system, and tree crowns was recorded. Additionally, changes in the species composition of forest stands before and after fires were analysed, particularly in relation to the ratio of fire-resistant to vulnerable species.

To identify the key characteristics of forest recovery processes, multiple areas with varying post-fire periods were surveyed. Changes in biodiversity and vegetation structure occurring during different stages of succession were assessed. The research was supported by the use of GIS technology, specialised online resources, and computer software, including Digitals 5.0 (Fire information for…, 2025).

Results

Analysis of statistical data from the relevant department of the Sumy Regional State Administration revealed that between April and October 2024, fires affected a total area of 339.92 hectares within the Northern Forest Office of the State Enterprise (SE) Forests of Ukraine. The majority of these fires were recorded in the Svesky forestry, where they covered an area of 242.08 hectares (Fig. 1). Additionally, fires were reported in the Okhtyrsky, Sumy, Lebedynsky, Krasnopilsky, and Shostka forestry districts. Between 19 September and 1 November 2024, within the Sumy Regional Municipal Agroforestry Enterprise Sumyoblagrolis, fires were registered over a total area of 314.85 hectares. The largest number of these occurred in SE Seredino-Budsky Agroforestry (240.2 hectares), followed by SE Nikolaevsky Agroforestry (40.7 hectares), SE Yampilsky Agroforestry (12.4 hectares), and SE Shostky Agroforestry (9.4 hectares).

An analysis of the response of forest ecosystems and their components to the effects of pyrogenic factors revealed that coniferous species, particularly *Pinus sylvestris*, were more vulnerable due to their high resin content. This characteristic facilitates rapid ignition and the spread of fire (Table 1). The study found that approximately 60% of pine forests in the affected areas were either destroyed or critically damaged. In contrast, deciduous species exhibited greater resistance to fire, with tree mortality rates reduced to 20-30%.



a *b*

Figure 1. Spread of fires in the territory of the Svesky Forestry Department and adjacent territories

Note: a) data for September 2024; b) for October 2024

Source: created by the authors

Table 1. Comparison of damage to forest-forming species after fires

Parameter	*Pinus sylvestris*	*Quercus robur, Acer platanoides*
Percentage of dead trees	60% of the total number of trees	20-30% of the total number of trees
Cortical damage	65% of trees with damage to more than 50% of the bark area	37% of oaks, 42% of maples with bark damage
Trunk damage	70% of trees with significant trunk damage	35% of oaks, 20% of maples with trunk damage
Crown damage	80% of trees with crown damage	43% of oaks and maples had crown damage

Source: created by the authors

Pine trees exhibited the greatest degree of bark damage, with 65% of individuals suffering damage to more than 50% of their bark, ultimately leading to their gradual decline. In contrast, deciduous trees were less affected, with only 37% of oaks and 42% of maples experiencing significant bark damage.

Conifers also showed higher levels of trunk damage, recorded in 70% of affected trees. By comparison, damage to the trunks of oak and maple trees was considerably lower, with only 35% of oaks and 20% of maples exhibiting such negative effects. The root systems of trees were also severely impacted by fire. In pine forests, 70% of trees suffered root damage at depths of up to 30 cm, significantly limiting their ability to recover. Deciduous species, particularly oak and maple, demonstrated greater resilience to root damage, with only 30% of oaks and 20% of maples sustaining significant harm, allowing for faster post-fire regeneration.

The tree crown is a critical component for growth, and its damage can substantially reduce a tree's ability to regenerate. Among pines, 80% of trees experienced crown damage, leading either to their death or a significant reduction in growth rate. In contrast, only 43% of oak and maple trees exhibited crown damage, highlighting their greater resistance to fire. Thus, the analysis of fire impact on forest-forming species indicates that coniferous species, such as pine, are significantly more vulnerable to thermal stress. Deciduous species, such as oak and maple, exhibited markedly higher resistance, which can be attributed to their thicker bark, stronger trunk structure, and more developed root systems. These findings suggest that effective forest ecosystem management in areas with heightened fire risk should incorporate recovery strategies that account for species-specific characteristics.

Within the study region, an analysis of fire impact on different age groups of trees was also conducted. The greatest losses were observed among young stands, as immature trees lacked sufficient resistance to high temperatures. In the forests surveyed, more than 80% of young trees under the age of 10 perished following the fire, with young pines being particularly vulnerable (Table 2).

Table 2. Changes in age and spatial structure after fires

Indicator	Young trees (up to 10 years old)	Middle-aged trees (10-30 years old)	Old trees (over 30 years old)
Percentage of dead trees	80% (especially among pines and maples)	50%	40% (mainly among conifers)
Trees saved after fire	20%	50%	60% (mostly oaks and maples)
Loss of diversity of age groups	High	Moderate	Low
Increasing forest fragmentation	35% of the total forest area	20%	15%

Source: created by the authors

Older oaks and maples demonstrated greater resilience, with approximately 40% of individuals sustaining only minimal damage. Among trees older than 30 years, deciduous species exhibited a higher survival rate compared to conifers. This can be attributed to the thick bark of mature oaks, which provides protection for internal tissues against thermal effects, as well as their more developed root systems. The decline in age group diversity following fires was evident, as young trees – typically crucial for forest regeneration – were almost entirely eliminated in the affected areas.

The analysis revealed that fires have the capacity to alter the species composition of the woody layer in forest ecosystems, leading to a higher representation of fire-resistant species while reducing the proportion of vulnerable plants. Fires also had a significant impact on the grass-moss layer, primarily due to direct destruction, which exceeded 40% in some areas (Fig. 2). Additionally, in certain locations – particularly on slopes – the disappearance of the living topsoil led to an acceleration of soil erosion processes. These transformations, characterised by a reduction in species diversity and a simplification of ecosystem structure, ultimately result in a diminished capacity of the forest to withstand adverse external factors.

Figure 2. Fire and its consequences in one of the deciduous forest areas

Source: created by the authors

The restoration of forests following fires is a critical issue. In general, this process is complex and multi-stage, often spanning several decades and influenced by numerous factors, including forest type, fire intensity, climatic conditions, and soil quality. Within the studied region, significant differences were observed in the speed and nature of recovery between coniferous and deciduous forests. However, the following stages of restoration were typically well-defined: initial restoration (1-3 years); development of pioneer species (3-7 years); formation of a young stand (7-15 years); ecosystem stabilisation (over 15 years).

Coniferous forests, particularly pine stands, exhibited a slower rate of recovery, whereas deciduous forests regenerated more rapidly. Within the first three years following a fire, active regeneration was observed in 60% of the affected areas in deciduous forests (Table 3). In contrast, coniferous forests showed significantly slower recovery, with only 30% of the affected area demonstrating signs of regeneration during the same period. Additionally, the recovery of pine forests was further hindered by the widespread occurrence of species replacement processes and the increased prevalence of pests and diseases, which further complicated and slowed down their restoration (Fig. 3).

Table 3. Comparison of natural regeneration rates of coniferous and deciduous forests

Parameter	Coniferous forests	Deciduous forests
Starting the recovery	In 2-4 years	In 1-2 years
Area recovered in 3 years	30%	60%
Average time for formation of a young stand	8-10 years	5-7 years
Area recovered in 10 years	50-60%	80%

Source: created by the authors

Figure 3. The current state of a pine forest area that in 2008 became a hotbed of grass fire spread and subsequent intensification of the impact of the top bark beetle
Source: created by the authors

Natural forest recovery following fires typically takes between 10 and 20 years, depending on forest type. However, repeated fires or adverse environmental conditions can significantly extend this period, necessitating the development of long-term strategies to enhance ecosystem resilience. In designing these strategies, it is essential to consider that fires contribute to increased fragmentation of forested areas.

Forest fragmentation is a particularly pressing issue in northeastern Ukraine, as demonstrated by research conducted even before the large-scale invasion of the Russian Federation in the Novgorod-Siverskyi Polissya region. In accordance with the principles of island biogeography, the perimeter-to-area ratio (P/A) and its reciprocal (A/P) were used as key indicators in analysing fragmentation levels. These criteria complement each other: P/A primarily characterises territorial structures (in this study, forested areas) in terms of their linear dimensions and provides insight into the ecological permeability of their boundaries. A/P focuses on the size of forest patches and reflects their ecological optimality. A higher A/P value suggests increased ecological stability, as it indicates a greater distance between the core and the peripheral (external) edges of the area. A high level of ecological stability is associated with areas where A/P exceeds 1 km^2/km and P/A remains below 1 km/km^2.

The research findings indicate that even within one of the most forested regions of Ukraine – Novgorod-Siverskyi Polissya, where forest cover was approximately 20% at the time of the study – the A/P values for forest massifs predominantly ranged from 0.1 to 0.4 km^2/km, while P/A values varied between 3 and 8 km/km^2. The highest recorded A/P values reached 0.7-0.8 km^2/km, while the lowest P/A values ranged between 1.2 and 1.4 km/km^2. However, some forest massifs exhibited significantly higher levels of fragmentation, with A/P values dropping as low as 0.02-0.03 km^2/km and P/A increasing to 39.9-55.2 km/km^2. These findings objectively demonstrate a high degree of forest fragmentation, a high ecological permeability of forest boundaries, and a low level of protection for interior areas from both natural and anthropogenic disturbances. In the context of increased fire activity, further reductions in A/P values and increases in P/A values (typically within a 10-30% range) have been recorded across forest areas. This trend indicates an increasing degree of forest fragmentation, heightened permeability of forest phytocenosis boundaries, and a more pronounced clearing effect.

One of the ecological consequences of increased forest fragmentation – even in the absence of fires – is a significantly heightened likelihood of invasive species colonising forest phytocenoses. These species are often not typical of undisturbed natural ecosystems and can alter the structure and stability of local flora populations. Due to the high permeability of forest boundaries and the widespread manifestation of the clearing effect, conditions emerge that facilitate processes such as synanthropisation, adventitisation, and therophytisation – all of which are indicators of geosystem disturbance. The ecological transformations resulting from high forest fragmentation have the potential to disrupt the entire system of ecological-coenotic interactions within the ecosystem. This can negatively impact populations of forest-forming species, alter cohort structures in younger tree generations, and hinder natural regeneration processes – including in areas previously affected by fires.

Discussion

The study confirmed that fires cause significantly greater losses among coniferous species compared to deciduous species, with Pinus sylvestris being the most vulnerable. The results indicated that 70% of pine root systems were severely damaged, and tree crowns were destroyed in 80% of cases. These findings align with those of S. Sydorenko *et al.* (2021), who noted that pines are among the most fire-prone tree species due to their high flammability. Similar conclusions were drawn by A.C. Scheper *et al*. (2021), who emphasised the need for active intervention in the restoration of coniferous forests, as natural regeneration processes alone are insufficient under conditions of frequent wildfires.

In contrast, deciduous species such as oak and maple demonstrated significantly greater fire resistance. In this study, only 20-30% of deciduous trees suffered critical damage, a finding consistent with S.-P. Zeng *et al*. (2020), who highlighted that the morphological characteristics of deciduous trees contribute to their increased fire resilience. The results obtained suggest the importance of promoting mixed stands, where coniferous and deciduous species coexist to enhance overall ecosystem resilience. This is supported by the research of T. Ramiadantsoa *et al*. (2023), who found that mixed forests are more capable of withstanding fires and recovering more rapidly due to a combination of diverse regeneration strategies.

The study also analysed the impact of fires on different layers and components of the forest phytocenosis. It was observed that fires cause significant changes at the level of the living aboveground cover, often leading to its destruction. One of the key consequences of this is the acceleration of erosion processes and the deterioration of conditions for tree growth. These findings align with the conclusions of S. Meilleur *et al.* (2022) and A. Siwach *et al.* (2021), who noted that the recovery of mosses can take more than five years and plays a crucial role in soil stabilisation and moisture conservation. Similarly, Z.H. Aliyev & F.F. Suleymanova (2022), along with Y. Fu *et al.* (2022), highlighted that soil degradation resulting from fires often serves as a limiting factor in the restoration of grass cover in forest ecosystems.

Fires significantly influence forest regeneration processes by regulating the quantitative and qualitative composition of litter and living aboveground cover, as well as by facilitating substrate mineralisation (Skydan *et al*., 2021). In particular, regarding *Pinus sylvestris*, it has been established that the impact of fire on natural regeneration can be both positive and negative, depending on the type of fire (crown or surface) and its intensity. At present, climate change is further contributing to the occurrence and spread of fires (Bayegizova *et al*., 2024). Rising temperatures and decreasing precipitation not only increase fire risks but also complicate regeneration processes. These challenges necessitate the development of adaptive approaches to forest resource management, as emphasised by J. Lecina-Diaz *et al.* (2021) and M. Sample *et al*. (2022).

One of the most serious consequences of forest fires is the increased fragmentation of forest areas, exacerbating an already significant issue, as research has shown that fragmentation is a concern even in regions with relatively high forest cover. The link between fires and increased fragmentation is further supported by the study of D. Armenteras *et al*. (2021), who investigated forest ecosystems and found that frequent fires contribute to the fragmentation of forested landscapes. The resulting loss of connectivity between forest patches slows natural succession processes, as plant seeds and pollinators struggle to disperse effectively across isolated areas.

Additionally, R. Halbac-Cotoara-Zamfir *et al.* (2022) highlighted that in highly fragmented environments, the risks of soil degradation and the spread of invasive species increase, as such species can rapidly colonise burnt areas. Their study also found that isolated forest patches, lacking connections to larger forested areas, exhibit limited natural recovery potential. These findings underscore the urgent need for active management strategies to reduce fragmentation and establish ecological corridors to enhance ecosystem connectivity.

Research by J. Hilty *et al*. (2020), and T. Zhai & L. Huang (2022) has demonstrated that creating ecological corridors between fragmented forest areas significantly improves ecosystem recovery by facilitating species migration and providing access to essential resources. These corridors also mitigate the risk of genetic isolation, a common consequence when species populations become confined to small forest patches. The preservation of ecological corridors is therefore a key component of modern landscape management strategies, particularly in light of climate change and the increasing frequency of wildfires (Matkivskyi & Taras, 2024). Furthermore, L. Li *et al.* (2021) suggested that an important area for future research is the impact of distance between fragmented forest patches on biodiversity recovery rates and overall forest viability.

Thus, reducing forest fragmentation and creating ecological corridors are essential priorities in modern forest management. Restoring connectivity between forested areas facilitates faster natural regeneration, reduces biodiversity loss, and enhances ecosystem resilience to future fires (Lozinska *et al.*, 2024; Tykhonova *et al.*, 2024). Developing networks of ecological corridors that link isolated areas is crucial for ensuring the long-term stability and functionality of ecosystems.

The findings of this study open several promising avenues for further research aimed at improving forest management and enhancing ecosystem resilience to wildfires. One key area of focus is the optimisation of mixed forest stand composition. It was found that combining coniferous and deciduous species helps reduce ecosystem vulnerability to fires and supports more sustainable post-fire recovery. The study by D.A. MacLean & K.L. Clark (2021) confirms that mixed forests are more resistant to external stressors, as deciduous species inhibit the spread of fire, while conifers contribute to the long-term stability of forest ecosystems. These findings suggest that continued research is needed to identify optimal species combinations adapted to local climatic conditions.

Another important research direction is the restoration of not only the tree stand but also other components of the forest ecosystem, particularly mosses and lichens (Biyashev *et al.*, 2024). The results of M.A. Bowker *et al.* (2023) indicate that the recovery of mosses and lichens is a long-term process, often taking several years. This highlights the need to develop new approaches to accelerate the regeneration of these vital ecosystem components.

Overall, the findings confirm that fires have a profound impact on forest ecosystems, particularly on coniferous forests. The increasing frequency of wildfires due to climate change necessitates adaptive management strategies that focus on reducing forest fragmentation, restoring all components of forest phytocenoses, and strengthening ecosystem resilience. In the context of ongoing climate change, an urgent priority is the improvement of fire prediction models and the assessment of their impact on forest stands, ensuring more effective mitigation and response strategies.

Conclusions

The study found that forest fires had a significant impact on forest ecosystems in northeastern Ukraine between 2022 and 2024. The key findings indicate that coniferous species were particularly vulnerable to fire, primarily due to their high resin content and structural characteristics. In contrast, deciduous species, particularly *Quercus robur* and *Acer platanoides*, exhibited higher fire resistance. This resilience can be attributed to their thicker bark and/or ability to regenerate quickly. Although local damage was observed in these species, their resistance helped maintain a certain level of ecological balance after fires. It was also determined that the lower layers of the forest suffered significant damage, including direct destruction, which in turn increased the risk of soil erosion. Furthermore, forest fragmentation in the studied regions has intensified, exacerbating ecological disruptions.

In light of these findings, it is crucial to implement active restoration measures, including promoting natural regeneration, afforestation, and the creation of ecological corridors. These actions will help mitigate the effects of fragmentation and restore ecological connectivity between isolated areas.

Looking ahead, it is also recommended to develop adaptive forest management strategies that account for the increasing frequency of fires, both due to natural factors (such as climate change) and anthropogenic influences. In the northeastern part of Ukraine, the spread of fires caused by military actions presents a particularly pressing challenge, characterised by unique complexities and a higher degree of environmental impact. Effectively managing such territories requires considering not only the ecological dynamics and functional patterns of forest ecosystems but also security-related factors. Military activity represents a powerful driver of environmental transformation, contributing to severe soil degradation and contamination with pollutants associated with explosives and their combustion by-products. Addressing these challenges should be integrated into policy frameworks and programme documents focused on post-war restoration efforts for Ukraine's natural complexes.

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Вплив лісових пожеж на лісові екосистеми

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Анотація. Пожежі спричиняють суттєві зміни в структурі лісів, порушують екологічні зв’язки та впливають на процеси відновлення. Метою дослідження було оцінити ступінь пошкоджень деревних насаджень та порівняти стійкість хвойних та листяних порід до пожеж. Проаналізовано вплив цих явищ на різні типи деревних порід та функціонування лісових екосистем у межах північно-східної України, яка у 2022-2024 роках зазнала масштабних пожеж. Аналіз охоплював вивчення ушкоджень кори, стовбура, кореневої системи та верхівок дерев, а також оцінку природних сукцесійних процесів. Хвойні породи, такі як *Pinus sylvestris* L., виявилися найбільш уразливими: близько 60 % дерев були повністю знищені або серйозно пошкоджені, а 70 % кореневих систем втратили здатність до відновлення. Верхівки були знищені у 80 % випадків, що призвело до зменшення щільності деревостанів. Натомість листяні породи, такі як дуб і клен, продемонстрували вищу стійкість до пожеж, зокрема лише 20-30 % цих дерев зазнали серйозних ушкоджень, і більшість із них успішно відновилися завдяки порослевому відновленню. Важливу роль у стабілізації ґрунтів відіграють мохи та лишайники, які постраждали найбільше – їхня кількість скоротилася більше ніж на 40 %. Це порушило природні сукцесійні процеси та вплинуло на відновлення лісів. Пожежі також збільшили фрагментацію лісових масивів. Це підкреслює загальну важливість створення екологічних коридорів та покращення зв'язності між лісовими масивами для полегшення природного відновлення. Рекомендовано також розробляти адаптивні стратегії управління лісами з урахуванням підвищення частоти пожеж, як наслідку протікання природних процесів (змін клімату тощо), так і антропогенних. Показано, що для північно-східної частини України особливо актуальним є питання поширення пожеж, обумовлених впливом воєнних дій. Визначення тактичних та стратегічних підходів щодо управління такими територіями вимагає врахування не лише особливостей та закономірностей функціонування власне лісових екосистем, а й аспектів безпекової ситуацій та того, що воєнні впливи виступають додатковим потужним чинником трансформації та забруднення довкілля. Окреслення підходів до розв'язання зазначеного питання має стати частиною програмних документів, пов'язаних із повоєнним відновлення природних комплексів України

Ключові слова: біорізноманіття; екологічна фрагментація; сукцесійні процеси; дистанційне зондування; стабілізація ґрунтів; адаптивне управління лісами

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The influence of *Robinia pseudoacacia* plantations on soil in the park areas of Dnipro city contaminated with heavy metals

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Abstract. The aim of this study was to investigate the soil condition of recreational park areas in Dnipro city on chromium, nickel and cobalt contents and the ability of various components of black locust's aboveground biomass to accumulate these contaminants. An excess of the maximum permissible concentration (MPC) of chromium (2.1-4.3) and nickel (1.5-3.5) was recorded in the studied soils of recreational plantings in all experimental sites. Cobalt concentrations exceeded MPC only in two experimental sites: Oles Honchar Dnipro National University Botanical Garden and Green Grove Park (1.4-1.5). It was compared the metal concentrations in the vegetative (leaves, trunk) and generative (fruits) organs of *R. pseudoacacia* and in the soil beneath a tree canopy of the plantings. Chromium concentrations in aboveground biomass corresponded to the range of 0.10-11.67 mg · kg^{-1}, the highest concentration of this metal occurred in assimilation fraction. The highest accumulation of nickel was recorded in fruits, where its highest concentration was equal to 8.46 mg · kg^{-1}. Cobalt had the lowest concentration values among the metals studied; the range of its content was 0.09-0.21 mg · kg^{-1}, and it had almost the same concentration level in the biomass of trunk wood, leaves and fruits. The biological accumulation factor (BAF) was calculated to determine the deposit potential of *R. pseudoacacia*. According to the obtained values of BAF, it should be noted that bioconcentration was not occurred for all the studied metals. *R. pseudoacacia* is able to function optimally in urban soils of park areas with a rather wide ranges of chromium, nickel and cobalt concentrations. Due to low values of BAF, this tree species is not susceptible to accumulate the metals in such concentrations that can pose a risk for the use of this species in recreational plantings of industrial city parks

Keywords: soil pollution; chromium; nickel; cobalt; biological accumulation factor

Introduction

Due to the increasing anthropogenic pressure on urban ecosystems, which leads to the accumulation of toxic substances in soils, particularly heavy metals such as chromium, nickel, and cobalt. These contaminants pose serious environmental and health risks, as they are persistent, non-biodegradable, and capable of entering the food chain. Today, various approaches and effective technologies are used, which both directly and indirectly affect the intensity of accumulation of heavy metals by reducing their mobility and availability to plants (Kharytonov *et al.*, 2021).

Park zones, serving as critical recreational spaces in cities, often experience significant exposure to pollution from surrounding industrial activities, transport emissions, and urban runoff. Certain tree species are capable of absorbing, translocating, and accumulating heavy metals in their biomass, thus acting as natural phytoremediators that reduce the bioavailability of pollutants in the soil. Understanding these processes contributes to the creation of sustainable and safe recreational environments, enhances the ecological functions of urban green spaces, and informs the design of planting schemes aimed at restoring the physical and chemical properties of degraded soils.

The most common transformation of environment is soil contamination with heavy metals, acidification and, in extreme cases, destruction of the soil cover. Metal elements are considered to be actual and widespread soil pollutants. According to V. Zverkovskyy *et al.* (2018), the annual volume of heavy metal emissions in the Dnipro region has been in the range (tons · year^{-1}) 774.9-618.6, of which

Cr was 4.9-11.4 and Ni was 3.0-7.6. When metal-containing aerosols fall out onto the land and plant surfaces, the degree of their ability to be incorporated in the trophic links of ecosystems depends on a significant number of factors. Therefore, systematic environmental monitoring, assessment of soil condition in urbanised and recreational areas of industrial cities should serve as the basis for the development of an action plan aimed at optimisation of the soil properties (namely granulometric composition, physico-chemical, biological properties) (Bobunov *et al.*, 2023).

The technology of creating a net of plantings which will have remediation properties is one of the methods most appropriate to restore the corresponding fertility characteristics to contaminated soils. Native and non-native plant species that are used in plantings of recreational areas of industrial cities should have broad environmental tolerance in order to function and realise self-remediation potential. Plantings of tree species are particularly valuable, as they have a long-life cycle, and their significantly developed crown biomass can serve as a place of deposition of pollutants that remain in the aboveground biomass for a long time. *Robinia pseudoacacia* L. is one of the most suitable species with broad ecological valence and remediation potential. An urgent issue is the research of its ability to absorb inorganic metal contaminants from the soil and retain them in the biomass of different tissues, since plant body tissues, being different compartments of biomass, have different degrees of potential ability to absorb and accumulate pollutants (Kunakh *et al.*, 2024).

Z.F. Wang *et al.* (2023) noted that along with other tree species, *R. pseudoacacia* is widely used for urban green spaces, mainly because of its high adaptive potential and ecosystem services. In particular, studies have shown that *R. pseudoacacia* demonstrates a fairly high resistance in the urban environment. However, in general, and in the context of creating green landscaped areas, in particular, Robinia is widely used as a soil improver, with nutrients such as magnesium, calcium. According to N. Yiğit (2024), this plant can reduce soil contamination with tin and molybdenum, as well as copper and lead (Băbău *et al.*, 2024). H.A. Ergül & I.S.K. Kuşçu (2024) found that *R. pseudoacacia* is the best phytoremediator of strontium from soils in copper mining areas compared to other species studied.

An important issue is the degree of accumulation of potentially toxic compounds and their further translocation due to the aboveground biomass production, part of which (trunk, crown) performs a long-lasting binding of pollutants, and other fraction (leaves, fruits) is able to enter the soil and thereby partially return potentially toxic compounds. V. Lovynska *et al.* (2023) presented the studies on the level of soil contamination with heavy metals (Zn, Cu, Cd, Pb) and the processes of their accumulation by native and non-native tree species in green spaces of Dnipro city. The ranges of average heavy metal concentrations in the various experimental sites of the city's green infrastructure were as follows ($mg \cdot kg^{-1}$) 30.7-185.5 for Zn, 5.7-22.4 for Cu, 9.0-31.3 for Pb, and 0.213-0.598 for Cd. Heavy metal accumulation in the leaf fraction of R. *pseudoacacia* was noted to be occurred in the following descending order: Zn > Cu > Pb > Cd. Authors noted determination of relationships between concentrations of potentially toxic metal elements in atmospheric air of Dnipro city and in the assimilation organs of *R. pseudoacacia* trees. Among the studied pollutants, the maximum concentration in the assimilation organs was found for Zn, the range of which was 15-30 $mg \cdot kg^{-1}$. Almost the same accumulation level was recorded for Cu and Pb: 3.9-17.2 $mg \cdot kg^{-1}$ and 8.6-10.8 $mg \cdot kg^{-1}$ respectively. The presence of Cd, as a non-essential element for plants, allows us to consider

R. pseudoacacia plantings as a potential depositor of this metal in the conditions of industrial cities where polyelement pollution occurs.

C. Zou *et al.* (2024) demonstrated that in urban green spaces the average soil organic carbon was 8.47 mg · ha^{-1} and concurrent with moderate heavy metals pollution with Ni 32.03-33.50 mg · kg^{-1}; Pb 27.93-29.65 mg · kg^{-1}; Cu 26.97-41.20 mg · kg^{-1}. The concentration of heavy metals in urban green spaces determined by the historical usage of the land, with escalation correlating with the duration of land utilisation history. D.L. Brkovic *et al.* (2021) determined the concentrations of metals (Mn, Ni, Ca, Mg, Fe, Zn, Cr, Pb, Cd, Cu) in the soil of fast-growing plant species (*Populus nigra* L., *Fraxinus ornus* L., *Salix alba* L., *Salix caprea* L.) (Serbia). The *F. ornus* species exhibits the ability to phytoextract Ca, the *P. nigra* species – Zn, Ca and Cd, while both *Salix* species have the ability to phytorecover Zn and Ca. As summarised the authors, S. alba is an effective bioaccumulator of Mn, Fe, Cr, Pb, Zn and Ca, *S. caprea* – Fe, Cu, Cr, Mg and Pb, and *P. nigra* – Mn and Cd. The authors recommend taking this into account when selecting plant species suitable for remediation.

Taking into account the significant remediation potential, wide distribution of *R. pseudoacacia* in recreational plantings of park areas of Dnipro city, the growth of this tree species in soils with varying degrees of pollution, the issue of the ability to absorb and accumulate metal elements in various components of aboveground biomass is relevant and requires further development.

The main objective of this research was to establish the ability of *R. pseudoacacia* trees to absorb and accumulate in their biomass the metals taken up from the soils of recreational park areas in Dnipro city. For this, it was developed the following tasks:

1. to determine the degree of soil and aboveground biomass contamination by Cr, Ni, Co in recreational plantings of park areas;
2. to establish the potential of *R. pseudoacacia's* biomass for absorption and accumulation of Cr, Ni, and Co from the soil by biological accumulation factor.

Materials and Methods

The study was conducted in park areas of Dnipro city during the growing season: from May to October 2022. The study was conducted in accordance with the Convention on Biological Diversity (1992). Characteristics of experimental sites are given in Table 1.

Table 1. Locations of experimental sites in recreational plantings of parks in Dnipro city

Name of the recreation object	Park area, ha	Geographical coordinates	Height above sea level	Landscape type	Terrain element	Share of *R. pseudoacacia* in the park's plantings, %
Taras Shevchenko Central Culture and Leisure Park	45	48º27'42'' N 35º04'18'' E	90	Valley-adjacent gully	Right-bank slope, upper part, slope angle 3-4°	20
Lazar Globa Central City Children's Park	26	48º28'14'' N 35º01'31'' E	56	Valley-terrace	Floodplain	9
Park Sahaydak	34	48º29'08'' N 35º03'37'' E	55	Valley-terrace	Floodplain	15
Druzhby Park	90	48º32'07'' N 35º05'25'' E	79	Valley-terrace	Third terrace	15

Table 1, Continued

Name of the recreation object	Park area, ha	Geographical coordinates	Height above sea level	Landscape type	Terrain element	Share of *R. pseudoacacia* in the park's plantings, %
Metallurgists Square	3.8	48°28'26.00" N 34°59'31.00" E	65	Watershed-gully	Upland	50
Urban Youth Park recreation and leisure "Novokodatskyi"	35	48°29'13.43" N, 34°56'32.59" E	82	Valley-terrace	Upland Floodplain	25
Green Grove Park	53.6	48°26'10'' N, 35°00'35'' E	145	Watershed-gully	Ravine (plateau within the north-eastern slope)	16
Prydniprovsky Park	7	48°24'01" N, 35°07'56" E	75	Valley-terrace	Sandy terrace	35
Botanical garden of DNU	46	48°26'10'' 35°02'32'' E	127	Watershed-gully	Upland	27

Source: developed by the authors

Table 2 shows the characteristics of the soils in the park areas, in *R. pseudoacacia* plantations where experimental samples were selected. Soil classification and assessment of granulometric composition were carried out in accordance with the IUSS Working Group (2022). Nine sample points were taken to determine the soil physical and chemical properties and the content of chromium, nickel and cobalt. The sampling depth was 0-20 cm; the weight of each sample was about 300–350 g. Values of pH, total mineralisation, salinity, and electrical conductivity of soil samples were determined using a combined moisture-proof TDs/pH/EC/Salinity/Temp meter EZ9909A (Kelilong Electron, China). Samples of aboveground biomass of black locust trees were taken from each soil experimental site; there are a total of 27 samples were selected, and samples of trunk wood, leaves, and fruit biomass were averaged. The sampling and preparation procedures followed the instructions given in Mac Naeidhe (1995).

Table 2. Characteristics of park soils

Object name	Soil type	pH value	Total mineralisation, ppm	Salinity %	Electrical conductivity, mcs/cm
Taras Shevchenko Central Culture and Leisure Park	Calcic Chernozem (Siltic)	9.04	30	23	47
Lazar Globa Central City Children's Park	Calcic Chernozem (Siltic)	8.48	124	93	188
Park Sahaydak	Fluvisol (Loamic)	8.85	62	46	96
Druzhby Park	Calcic Chernozem (Siltic)	6.37	42	32	64
Metallurgists Square	Calcic Chernozem (Siltic)	8.82	31	23	48

Table 2, Continued

Object name	Soil type	pH value	Total mineralisation, ppm	Salinity %	Electrical conductivity, mcs/cm
Green Grove Park	Calcic Chernozem (Siltic)	9.09	50	39	78
Urban Youth Park recreation and leisure “Novokodatskyi”	Calcic Chernozem (Siltic)	7.44	424	321	644
Prydniprovsky Park	Anthrosol (Loamic)	6.57	39	30	61
Botanical garden of DNU	Calcic Chernozem (Siltic)	8.23	110	86	174

Source: developed by the authors

Heavy metal concentrations (Zn, Cu, Pb, Cd) in the soil was estimated using a modified aqua regia extraction method (Shahid *et al.*, 2017). According to this method, a 100-mg sample of fine soil dried at 105°C was mixed with 200 μL of water and four acids (900 μL of hydrochloric acid, 300 μL of nitric acid, 300 μL of hydrofluoric acid, and 150 μL of perchloric acid). The resulting mixture was treated with the microwave cleavage, then centrifuged (5000 rpm), and the supernatant was harvested to determine the concentration of the elements. Preliminary preparation of plant material samples for heavy metal detection included washing the biomass with distilled water, drying at room temperature for two weeks and at 105°C for 4 hours, followed by homogenisation. Dried leaf samples were ground to a fine powder using an ultra-centrifugal (Retsch Centrifugal Grinding Mill ZM 1000). 100 mg of each sample was mixed in centrifuge sample tubes with 200 μL of ultrapure water and 1.9 ml of 65% nitric acid. This mixture was incubated for 1 hour under a fume hood. Then the samples were mixed with 600 μL of aqueous solution of 4.8% hydrofluoric acid and put in a microwave oven for 1-2 hours. After processing in a microwave oven, the liquid phase of the supernatant was supplemented with ultrapure water. Prior to the direct measurement of element concentration in solutions, the samples were diluted 1:10. The concentration values of the samples were measured by mass spectrometry using an ICP-MS instrument (model X Series 2, Thermo Fisher Scientific, Dreieich, Germany). To assess the accumulation properties of the aboveground biomass of the studied tree species, bioaccumulation factors (BAF)s was calculated using the following formula:

$$BAF = [metal]_{biomass} / [metal]_{soil}, \qquad (1)$$

where: $[metal]_{biomass}$ is average metal content in part of the above-ground biomass, $mg \cdot g^{-1}$; $[metal]_{soil}$ is metal content in the substrate, $mg \cdot g^{-1}$ (Sekabira *et al.*, 2011).

Results and Discussion

According to the Hygienic regulations for the permissible concentrations of chemicals in soils (Order of the Ministry..., 2022), the maximum permissible concentrations (MPC, $mg \cdot g^{-1}$), of the mobile form are the following: 4.0 for nickel; 5.0 for cobalt; 6.0 for chrome (III) in comparison with Clark levels (background) (2.1.7.2511-09 “Approximate permissible concentrations of chemical substances in soils”). Figures 1-3 presented data on the actual concentrations of mobile forms of the studied metals in comparison with the standard data of the maximum permissible concentrations.

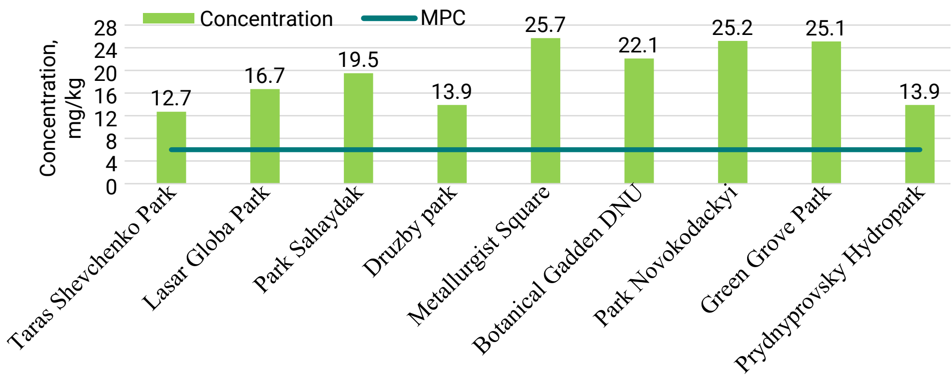

Figure 1. Chromium concentrations in the soils of recreational areas of Dnipro city
Source: developed by the authors

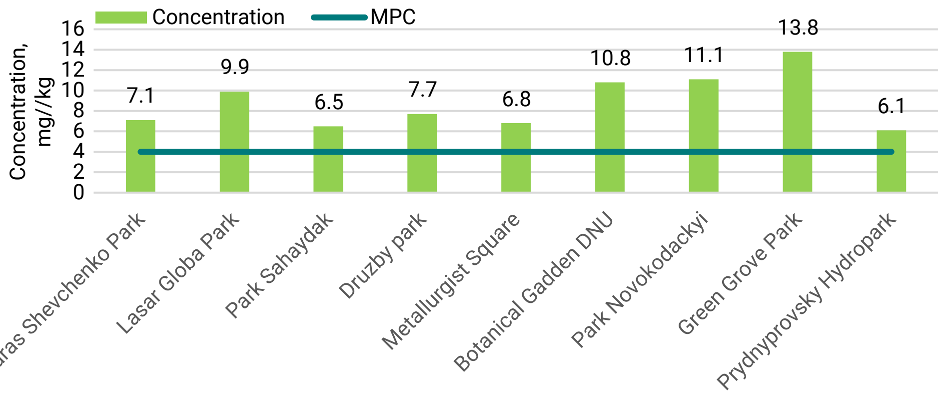

Figure 2. Nickel concentrations in the soils of recreational areas of Dnipro city
Source: developed by the authors

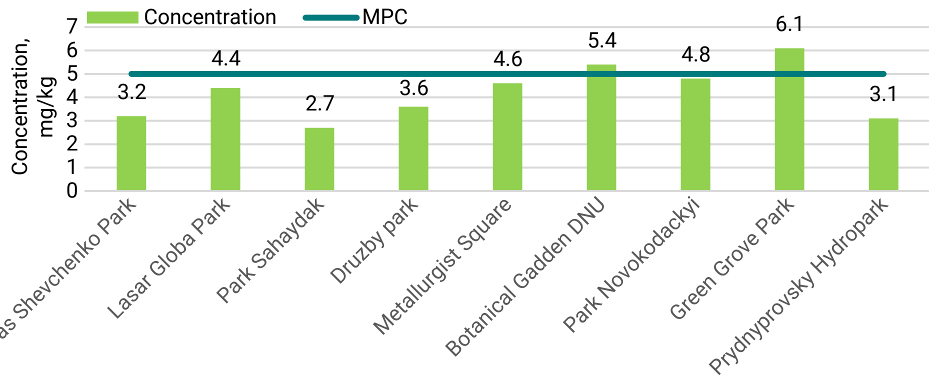

Figure 3. Cobalt concentrations in the soils of recreational areas of Dnipro city
Source: developed by the authors

In the studied soils of all recreational plantings, an excess of MPC of chromium was recorded, which corresponded to the range of 2.1-4.3 times. All the studied soils did not meet the standard values of nickel content, and exceeded the MPC by 1.5-3.5 times. A more favorable situation was observed for cobalt concentrations in the soils of recreational plantings, since a slight excess of MPC was recorded only in two experimental sites: Botanical Garden of DNU and Green Grove Park (1.4-1.5 MPC).

Heavy metal concentrations in the aboveground biomass of R. pseudoacacia trees. Formation of the elemental composition of plant biomass and the deposition of individual elements is influenced by numerous abiotic and biotic factors, among which soil physical and chemical properties are decisive and crucial. Results on metal element concentrations in various components of the aboveground biomass of *R. pseudoacacia* trees (in the trunk wood, leaves and fruits) are given in Table 3.

Table 3. Heavy metal concentrations in aboveground biomass fractions of *Robinia pseudoacacia*

Park name	Heavy metal concentration, $mg \cdot kg^{-1}$		
	Cr	Ni	Co
	Trunk wood		
Taras Shevchenko Central Culture and Leisure Park	0.14 ± 0.01	0.39 ± 0.01	0.10 ± 0.00
Lazar Globa Central City Children's Park	0.30 ± 0.01	0.32 ± 0.01	0.10 ± 0.00
Park Sahaydak	0.35 ± 0.01	0.77 ± 0.01	0.10 ± 0.00
Druzhby Park	0.22 ± 0.01	1.04 ± 0.02	0.10 ± 0.00
Metallurgists Square	0.17 ± 0.01	0.80 ± 0.01	0.10 ± 0.00
Botanical garden of DNU	0.65 ± 0.02	0.64 ± 0.02	0.15 ± 0.00
Urban Youth Park recreation and leisure "Novokodatskyi"	0.20 ± 0.01	0.57 ± 0.01	0.10 ± 0.00
Green Grove Park	0.30 ± 0.02	0.16 ± 0.01	0.10 ± 0.00
Prydniprovsky Park	0.10 ± 0.01	3.55 ± 0.01	0.10 ± 0.00
	Leaves		
Taras Shevchenko Central Culture and Leisure Park	3.5± 0.05	1.79 ± 0.01	0.09 ± 0.00
Lazar Globa Central City Children's Park	5.35 ± 0.05	2.98 ± 0.01	0.13 ± 0.00
Park Sahaydak	5.70 ± 0.05	3.22 ± 0.01	0.13 ± 0.00
Druzhby Park	4.89 ± 0.03	3.88 ± 0.01	0.17 ± 0.01
Metallurgists Square	4.94 ± 0.03	2.98 ± 0.01	0.13 ± 0.00
Botanical garden of DNU	5.63 ± 0.01	4.25 ± 0.02	0.21 ± 0.01
Urban Youth Park recreation and leisure "Novokodatskyi"	2.77 ± 0.02	2.34 ± 0.01	0.12 ± 0.00
Green Grove Park	11.67 ± 0.08	2.56 ± 0.01	0.11 ± 0.00
Prydniprovsky Park	3.51 ± 0.04	1.79 ± 0.01	0.09 ± 0.00
	Fruits		
Taras Shevchenko Central Culture and Leisure Park	0.46 ± 0.01	2.37 ± 0.01	0.10 ± 0.00

Table 3, Continued

Park name	Heavy metal concentration, mg · kg^{-1}		
	Cr	Ni	Co
	Trunk wood		
	Fruits		
Lazar Globa Central City Children's Park	0.43 ± 0.01	1.19 ± 0.01	0.10 ± 0.00
Park Sahaydak	1.27 ± 0.03	1.79 ± 0.00	0.10 ± 0.00
Druzhby Park	1.12 ± 0.02	5.91 ± 0.02	0.10 ± 0.00
Metallurgists Square	1.98 ± 0.01	2.38 ± 0.00	0.10 ± 0.00
Botanical garden of DNU	1.55 ± 0.01	4.00 ± 0.01	0.10 ± 0.00
Urban Youth Park recreation and leisure "Novokodatskyi"	0.67 ± 0.01	3.82 ± 0.02	0.10 ± 0.00
Green Grove Park	0.57 ± 0.01	1.65 ± 0.01	0.10 ± 0.00
Prydniprovsky Park	0.35 ± 0.01	8.46 ± 0.03	0.11 ± 0.00

Source: developed by the authors

Chromium concentrations in aboveground biomass corresponded to the range of 0.10-11.67 mg · kg^{-1}. The greatest concentration of this element occurred in the vegetation fraction. The physiological essentiality of nickel in plants is still a controversial issue, and the toxicity of its high concentrations is obvious. When MPC of nickel was exceeded in the studied soil, Ni was acquired minimal concentration in the trunk wood tissues of the studied trees equal to 0.32 mg · kg^{-1}. The greatest accumulation of nickel occurred in fruits, where its highest concentration was recorded to be 8.46 mg · kg^{-1}. It should be noted that the maximum concentration of this metal occurred in recreational plantings of the Prydniprovsky Park. Cobalt had the lowest concentration values among the studied metals, the range of its content was 0.09-0.21 mg · kg^{-1}, and it had almost the same concentration level in the biomass of trunk wood, leaves and fruits.

BAF represents the plant ability to regulate (to a certain extent) the absorption of inorganic contaminants from the environment and their further migration to vegetation and generative organs. Table 4 shows the calculated values of BAF of the studied metals in the "soil – trees" system.

Table 4. BAF values for heavy metals in aboveground biomass fractions of *Robinia pseudoacacia*

Park name	Heavy metal concentration		
	Cr	Ni	Co
	Trunk wood		
Taras Shevchenko Central Culture and Leisure Park	0.011	0.055	0.031
Lazar Globa Central City Children's Park	0.018	0.032	0.023
Park Sahaydak	0.018	0.118	0.037
Druzhby Park	0.016	0.136	0.028
Metallurgists Square	0.007	0.118	0.022
Botanical garden of DNU	0.029	0.059	0.028

Table 4, Continued

Park name	Heavy metal concentration		
	Cr	Ni	Co
	Trunk wood		
Urban Youth Park recreation and leisure "Novokodatskyi"	0.008	0.052	0.021
Green Grove Park	0.012	0.012	0.016
Prydniprovsky Park	0.007	0.581	0.032
Leaves			
Taras Shevchenko Central Culture and Leisure Park	0.036	0.333	0.031
Lazar Globa Central City Children's Park	0.026	0.120	0.023
Park Sahaydak	0.065	0.274	0.037
Druzhby Park	0.080	0.772	0.028
Metallurgists Square	0.077	0.350	0.022
Botanical garden of DNU	0.070	0.369	0.019
Urban Youth Park recreation and leisure "Novokodatskyi"	0.027	0.348	0.021
Green Grove Park	0.023	0.119	0.016
Prydniprovsky Park	0.025	1.385	0.036
Fruits			
Taras Shevchenko Central Culture and Leisure Park	0.277	0.252	0.028
Lazar Globa Central City Children's Park	0.320	0.302	0.029
Park Sahaydak	0.291	0.494	0.046
Druzhby Park	0.351	0.506	0.047
Metallurgists Square	0.192	0.438	0.028
Botanical garden of DNU	0.255	0.392	0.039
Urban Youth Park recreation and leisure "Novokodatskyi"	0.110	0.213	0.025
Green Grove Park	0.465	0.185	0.018
Prydniprovsky Park	0.213	0.156	0.019

Source: developed by the authors

The difference in BAF values allows detecting metal elements with a high and low level of translocation from the soil to the tissues of aboveground plant organs. According to the obtained values of BAF, we should note that the bioconcentration phenomenon was not observed for all the studied metals. The BAF values of the metals in all components of biomass of *R. pseudoacacia* did not exceed 1, which indicates a low ability to deposit the studied elements, even if their excess content in the soil (Shrivastava *et al.*, 2019).

Using GIS analysis methods, it was interpolated the calculated BAF, which was determined in the studied areas of recreational plantings of *R. pseudoacacia*. The application of the isoline method was the most appropriate to map the results of the study, since BAF is a continuous indicator. As a result, the maps were constructed that show the distribution of the calculated BAF of accumulation of chromium, nickel and cobalt in biomass of leaves and trunk wood over the territory of Dnipro city (Fig. 4-9).

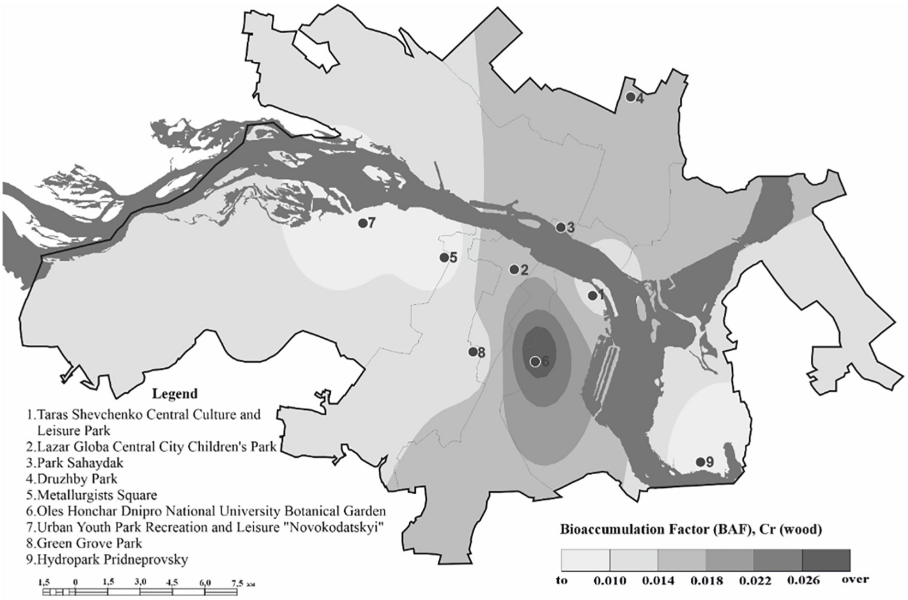

Figure 4. Chromium concentrations in the trunk of *Robinia pseudoacacia* plantings in Dnipro city
Source: developed by the authors

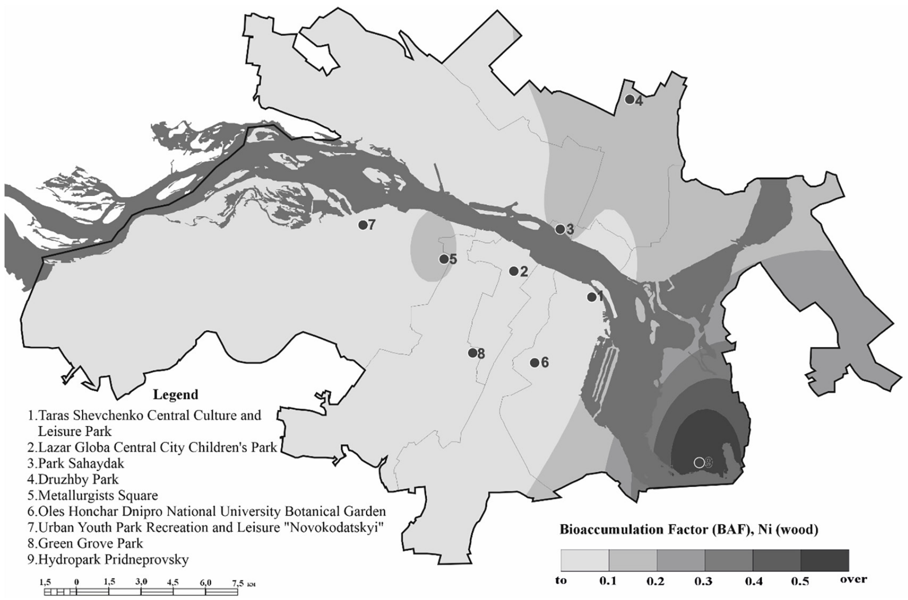

Figure 5. Nickel concentration in the trunk of *Robinia pseudoacacia* plantings in Dnipro city
Source: developed by the authors

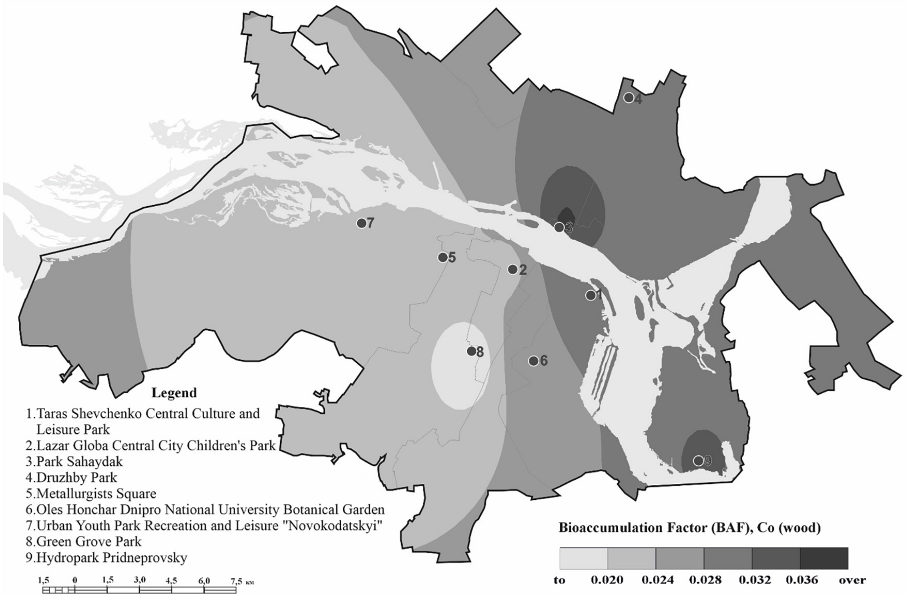

Figure 6. Cobalt concentrations in the trunk of *Robinia pseudoacacia* plantings in Dnipro city

Source: developed by the authors

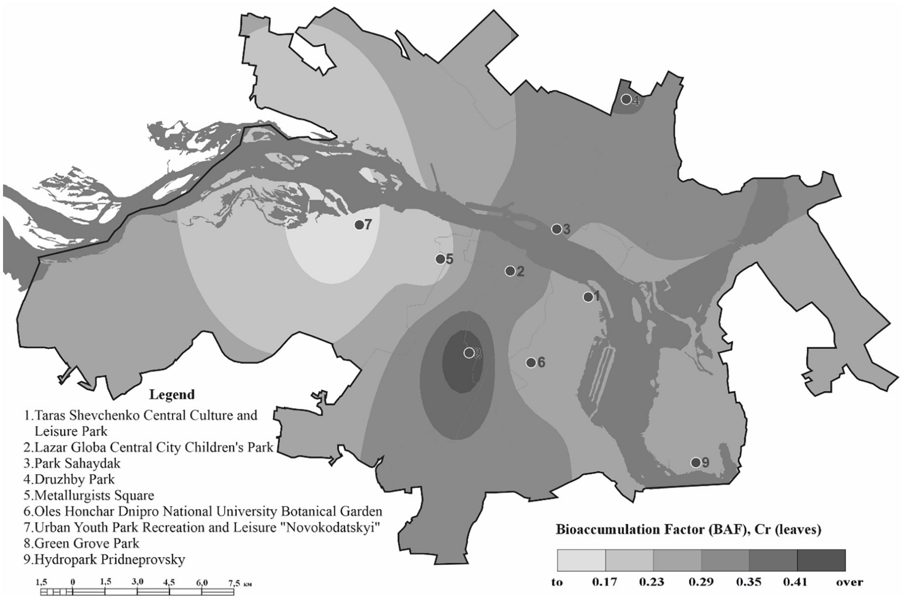

Figure 7. Chromium concentrations in the biomass fraction of leaves of *Robinia pseudoacacia* plantings in Dnipro city

Source: developed by the authors

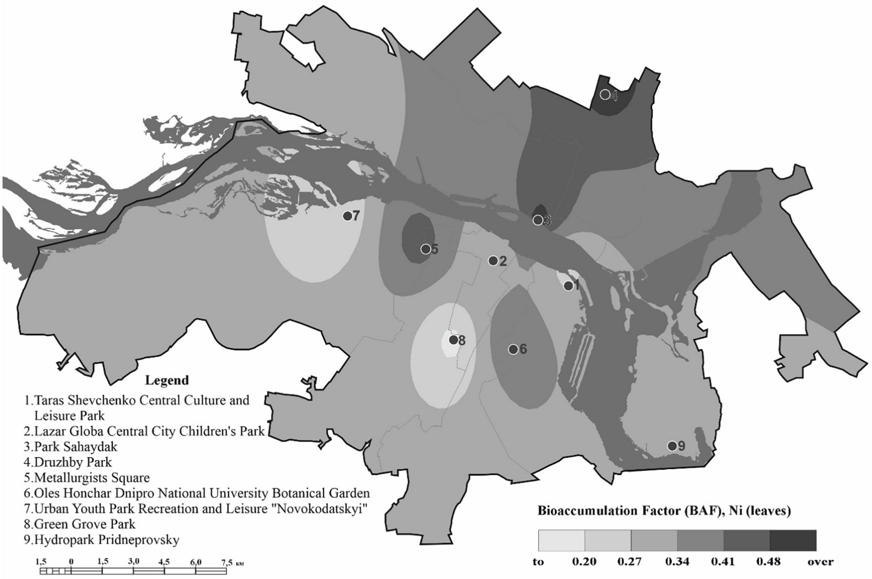

Figure 8. Nickel concentrations in the biomass fraction of leaves of *Robinia pseudoacacia* plantings in Dnipro city

Source: developed by the authors

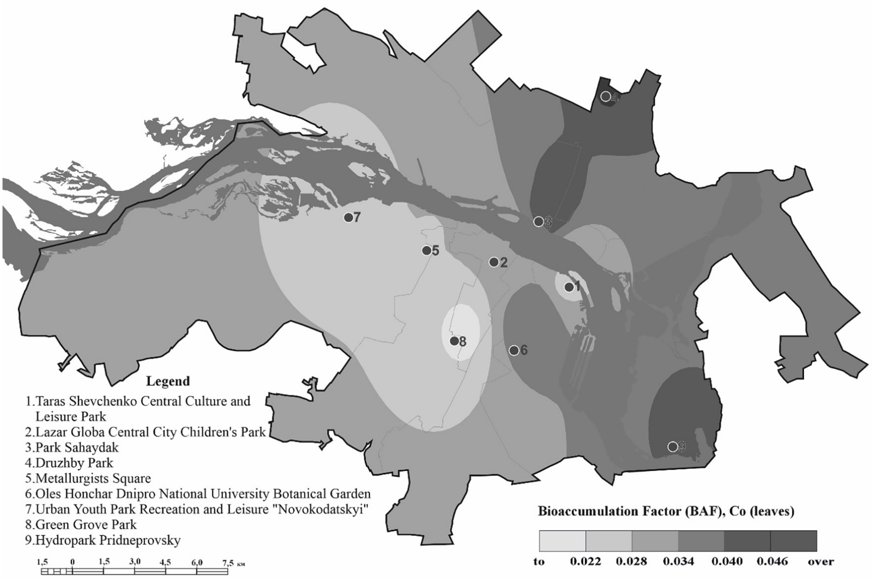

Figure 9. Cobalt concentrations in the biomass fraction of leaves of *Robinia pseudoacacia* plantings in Dnipro city

Source: developed by the authors

The constructed cartographic materials can be used to determine the potential ability of aboveground biomass of *R. pseudoacacia* trees to accumulate chromium, nickel and cobalt for any location of Dnipro city area**.**

The creation of remediation plantings in heavily polluted cities, selecting of non-native plant species ecologically suitable for recreational areas of industrial cities is the subject of research by both Ukrainian and foreign scientists. W. Yan *et al.* (2017) examined how *Robinia pseudoacacia* and *Amorpha fruticosa* rapidly adjusted their carbon balance strategies under repeated drought conditions. The study demonstrated species-specific physiological responses aimed at maintaining carbon homeostasis during environmental stress. Research by J. Banaszek *et al.* (2014) applied GIS techniques to analyse the spatial structure and ecological value of urban parks located in industrial areas. Their work highlighted landscape fragmentation and suggested planning improvements for urban green spaces. Z. Shi *et al.* (2021) developed a soil quality index to evaluate how *Robinia pseudoacacia* influenced soil health under various planting arrangements. The findings revealed that spatial configuration significantly affected soil properties and overall ecosystem function.

The functioning of tree species corresponding to microclimatic and edaphic conditions of park phytocenoses contributes to the intensification of the pedogenesis process and the formation of soil organic matter, which can ensure the balance of urban ecosystems and the economic feasibility of recreational plantings (Aman *et al.*, 2018). *R. pseudoacacia* is polymorphic tree species widely used for remediation of areas covered with degraded soils in Ukraine (Zverkovskyy *et al.*, 2018), Poland (Kraszkiewicz, 2016). In China this tree species has a wide ecological adaptability and adaptive capacity (Liang *et al.*, 2018; Yuan *et al.*, 2018). Under conditions of introduction, in the absence of care for plantings, *R. pseudoacacia* is able to intensively reproduce vegetatively and form monodominant communities; this species is naturalised exclusively in anthropogenically transformed landscapes (Kidawa *et al.*, 2021). However, in case of effective planting management, *R. pseudoacacia* effectively implements certain benefit functions, as anti-erosive, remediation, and quickly produces aboveground biomass (Grünewald *et al.*, 2009).

Because of presence of symbionts, nitrogen-fixing bacteria, *R. pseudoacacia* trees are able to fix nitrogen, which is crucial for nutrient-depleted soils. In addition, the plant litter of *R. pseudoacacia* has a favorable effect on the development of soil cover, since the litter enriches the nutrient-depleted soils in degraded ecosystems with the necessary micro- and macronutrients. These components mainly come from the *R. pseudoacacia's* litter that is being decomposed (Palowski *et al.*, 2016).

According to A.I. Anderson *et al.* (1972) in soils, concentrations chromium varied from excessive to toxic levels: 10 to 100 $mg \cdot kg^{-1}$. The mobility of nickel in the soil depends on the acid-base balance and the concentration of organic substances, mainly of humic acids. Nickel migration has a complex nature: on the one part, nickel enters the plant through soil solution; on the other part, its amount in the soil is replenished due to the destruction of soil minerals, the vegetation and bacterial die-off, as well as due to its entry with atmospheric precipitation.

Some authors note in their review that the toxic effects of chromium are associated with the formation of reactive oxygen species (ROS), which cause oxidative stress in plants (Ao *et al.*, 2022). The toxicity of Cr depends on the mechanisms of its uptake, translocation and subcellular distribution, as well as its effect on other plant metabolic processes, such as chlorophyll biosynthesis, photosynthesis and plant defence systems. Researchers A. Ekta & N.R. Modi (2018) indicated the existence of a mechanism for binding chromium ions in *R. pseudoacacia* roots, which inhibied its entry into the aboveground fraction and could explain the results obtained.

Cobalt belongs to the essential elements of plants that are involved in the formation of metalloenzymes. This metal activates enzyme systems, thereby participating in oxidative phosphorylation and photosynthesis, and is able to inhibit ethylene biosynthesis and increase plant drought resistance. The toxicity of elevated concentrations of this element is primarily associated with the development of oxidative stress and inhibition of assimilation.

Scientists A. Sharma *et al.* (2018; 2020) noted that some elements belonging to the heavy metals perform biogenic functions, such as activators of enzymes and structural components of metalloproteins. Nickel and cobalt are among such elements. At the same time, essential elements could show toxic effects when their concentrations exceeded those found as safe, which may be due to their gradual accumulation of heavy metals in the plant tissues.

Studies by Y.M. Li *et al.* (2003) conducted for herbaceous species of the genus *Alyssum* showed that these species hyperaccumulated Ni, but not Co. In this case, Ni uptake decreased at lower soil pH values and increased at higher soil pH values. According to A. van der Ent *et al.* (2018), a hyperaccumulative tree species such as *Glochidion cf. sericeum* (*Phyllanthaceae*) can simultaneously accumulate both nickel and cobalt in its leaves (until 1500 $\mu g\ g^{-1}$). The authors suggested that the hyperaccumulation of Co coincides with the hyperaccumulation of Ni, which occurs via similar physiological pathways. However, unlike Ni, which accumulates mainly in the cells of the leaf epidermis, the Co accumulation reaction consists of an extracellular mechanism.

A. Kabata-Pendias (2011) cited such concentrations of the studied elements that can cause toxic effects in plants ($mg \cdot kg^{-1}$): Cr – 0.02-0.20; Ni – 0.1-2.7; Co ⩾ 11.6. Comparing the obtained results on the concentrations of the studied elements, it should be noted that nickel concentrations in biomass exceeded the given concentrations which are considered to be phytotoxic, but no morphological damage was recorded in trees of recreational plantings. According to D. Środek & O. Rahmonov (2022), species-specific physiological and biochemical traits of the metabolism of the studied trees cause differences in the ability and degree of metal element accumulation in certain tissues of vegetative structural, assimilating and generative organs, regulating to a certain extent their intake from the soil. Comparing the results presented in the abovementioned paper, it can be seen that the BAF of Ni in the leaves similar to the range of the different location but the distribution the BAF values of Cr is lower.

Under the conditions of man-made pollution increase, the soils of urban areas need remediation and bringing of its indicators to the normative and sanitary standards. Therefore, the search for woody plants with hyperaccumulative properties that can absorb and keep heavy metals bound in plant tissues for a long time requires research into the phytoremediation properties of trees in regards to toxic heavy metals. The creation and restoration of green infrastructure should be based on the results of such studies.

Conclusions

An excess of the maximum permissible concentration of chromium (2.1-4.3 MPC) and nickel (1.5-3.5 MPC) was recorded in the studied soils of recreational plantings in all experimental sites. Cobalt concentrations exceeded MPC only in two experimental sites: Botanical garden of DNU and Green Grove Park (1.4-1.5 MPC).

Chromium concentrations in aboveground biomass corresponded to the range of 0.10-11.67 mg · kg^{-1}; the greatest concentration of this element was recorded in the assimilation fraction. The greatest accumulation of nickel occurred in fruits, where its highest concentration was recorded to be 8.46 mg · kg^{-1}. The minimum concentration of nickel was found in the woody part of the studied species 0.32 mg · kg^{-1}. Maximum concentration of nickel occurred in recreational plantings of the Prydniprovsky Park. Cobalt had the lowest concentration values among the studied metals; its range was 0.09-0.21 mg · kg^{-1}. The maximum value (0.21 mg · kg^{-1}) of this metal was found in the leaves which grows within Botanical garden of DNU. In general, almost the same concentration level in the biomass of trunk wood, leaves and fruits was found.

BAF values for metal elements in all components of the biomass of *R. pseudoacacia* did not exceed 1, which indicates a low ability to deposit the studied elements, even if their excess content in the soil. The highest BAF values were found in the case of accumulation of nickel in leaves and fruits of *R. pseudoacacia*.

A promising direction for further research is the application of the obtained cartographic materials to assess the potential capacity of *Robinia pseudoacacia* aboveground biomass for chromium, nickel and cobalt accumulation in urban recreational environments.

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Вплив насаджень робінії псевдоакації на ґрунт у паркових зонах м. Дніпро, забруднених важкими металами

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Анотація. Метою роботи було дослідження стану ґрунтів рекреаційних паркових зон м. Дніпро на вміст хрому, нікелю та кобальту, а також здатності різних компонентів надземної біомаси робінії псевдоакації до акумуляції цих забруднювачів. Перевищення гранично допустимої концентрації (ГДК) хрому (2,1-4,3) та нікелю (1,5-3,5) зафіксовано в досліджуваних ґрунтах рекреаційних насаджень на всіх дослідних ділянках. Концентрації кобальту перевищували ГДК лише на двох дослідних ділянках: в Ботанічному саду Дніпровського національного університету імені Олеся Гончара та парку «Зелений гай» (1,4-1,5). Проведено порівняння концентрації металів у вегетативних (листя, стовбур) та генеративних (плоди) органах *R. pseudoacacia*, а також у ґрунті під наметом дерев у цих насадженнях. Концентрації хрому в надземній біомасі відповідали діапазону

0,10-11,67 мг · кг$^{-1}$, найбільша концентрація цього металу спостерігалася в асиміляційній фракції. Найбільше накопичення нікелю зафіксовано в плодах, де його найвища концентрація дорівнювала 8,46 мг · кг$^{-1}$. Кобальт мав найнижчі значення концентрації серед досліджуваних металів, діапазон його вмісту становив 0,09-0,21 мг · кг$^{-1}$, причому він мав майже однаковий рівень концентрації в біомасі деревини, листках і плодах. Для визначення депонувального потенціалу *R. pseudoacacia* було розраховано коефіцієнт біологічного накопичення (КБН). Згідно з отриманими значеннями коефіцієнта, слід зазначити, що біоконцентрація відбувалася не для всіх досліджуваних металів. *R. pseudoacacia* здатна оптимально функціонувати в міських ґрунтах паркових зон з досить широким діапазоном концентрацій хрому, нікелю та кобальту. Зважаючи на низькі значення КБН, цей вид дерев не схильний до накопичення металів у таких концентраціях, які можуть становити ризик для використання цього виду в рекреаційних насадженнях індустріальних міських парків

Ключові слова: забруднення ґрунтів; хром; нікель; кобальт; коефіцієнт біологічної акумуляції

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Role of urban green spaces and tree plantations in improving ecosystem services and urban resilience

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Abstract. The study aimed to quantify the impact of urban green spaces on air quality, microclimate and climate resilience of cities. The study analysed the impact of urban green spaces on air quality, microclimate regulation and increasing the resilience of urban areas to climate threats. The article conducted a comprehensive analysis of the existing green areas in the five largest cities of Albania: Tirana, Durres, Shkoder, Vlora and Elbasan. To assess the ecosystem services of green spaces, measurements of the concentration of pollutants (CO_2, NO_2, SO_2, CO, PM2.5, PM10), temperature, humidity, and the soil composition and its ability to retain pollutants were analysed. The results showed that in areas with a high density of greenery, NO_2 and PM2.5 concentrations were reduced by 30-50%, indicating a significant air filtration capacity of trees. Temperature measurements demonstrated that park areas had 4-7°C lower temperatures than densely built-up areas, confirming their role in mitigating the urban heat island effect. In addition, soil analysis revealed a 15-25% reduction in Pb, Cd and Hg, which demonstrates the green areas' ability to naturally cleanse the environment. The green areas also retained 20-40% of precipitation, reducing the risk of flooding and increasing the water-holding capacity of the soil. The findings of the study highlight the need to integrate nature-based solutions into the urban management system to improve the sustainability of the urban environment. The data obtained can be used

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to develop recommendations for sustainable urban planning and justifying environmentally oriented approaches to the development of urban areas

Keywords: atmospheric pollution; air filtration; natural solutions; landscape planning; soil protection

Introduction

The research relevance is determined by the growth of urbanisation and its negative impact on the environmental condition of cities, which requires effective solutions to reduce climate and environmental risks. Increasing building density, shrinking green spaces and growing traffic are leading to deteriorating air quality, overheating of urban areas and a decline in biodiversity. In the context of climate change and increasingly frequent extreme weather events, the need to preserve and expand urban green spaces is becoming particularly important. The problem of this study is related to the insufficient consideration of ecosystem services of green spaces in urban planning, which leads to their reduction and decrease in their effectiveness in mitigating climate and environmental threats. In Albania, as in many other countries, rapid urbanisation is accompanied by a decrease in green spaces, which negatively affects the sustainability of the urban environment (Bollano, 2024). The impact of trees and parks on air quality, temperature regulation and prevention of climate hazards remains understudied, making it difficult to develop strategies for urban adaptation to climate change.

According to F. Aimar & K. Xhexhi (2024), the reduction of green space in Tirana increases the urban heat island effect and decreases air quality. The author emphasises that the integration of green areas into the urban environment is necessary to improve the microclimate and increase the sustainability of the urban ecosystem. J. Ademi (2021) noted that the ecosystem services of green spaces are substantial in reducing air pollution and temperature in cities. The author highlighted that the introduction of green spaces in public areas contributes to improving public health and increasing social activity. R. Plaku (2022) researched that compact pocket parks are an effective solution for greening densely built-up areas. These parks improve the local microclimate, increase biodiversity and improve the comfort level of the urban environment. As shown by S.L.R. Wood & J. Dupras (2021) tree species diversity in urban areas increases their climate resilience. However, the authors emphasise that increasing species composition requires careful management to avoid loss of ecosystem services such as air filtration and temperature regulation.

According to S. Lehmann (2021) renaturalisation and restoration of natural landscapes contribute to reducing flood risks and improving the water balance in cities. The author noted that the preservation of natural areas helps to strengthen the environmental sustainability of urban environments. As indicated by D.L. Evans *et al.* (2022), green infrastructure is substantial in improving air quality and reducing temperature in urbanised areas. The authors emphasise the need for an integrated approach to greening, including sustainable water and land management.

As emphasised by T. Semeraro *et al.* (2021) planning of urban green spaces should consider not only their aesthetic value but also their ecological functions. The authors noted that the effective distribution of green areas in the urban environment contributes to improving air quality, reducing temperature and increasing the psycho-physiological comfort of residents. According to the study by J.C. Bikomeye *et al.* (2021), investments in urban green spaces are especially important in times of environmental and social crises. The authors highlighted those green spaces not only increase the climate resilience of cities but are also substantial in ensuring social justice by providing equal access to ecosystem services. L.J. McCarthy & A. Russo (2023) noted that the introduction of nature-oriented solutions and the involvement of citizens in the management of green areas improves the perception of the urban landscape and increases the sustainability of ecosystems. The authors emphasise that the interaction of residents with green spaces contributes to their environmental education and the development of urban environments adapted to climate change. As shown by F. Ungaro *et al.* (2022), soil ecosystem services in urban green spaces are instrumental in maintaining water balance and reducing soil contamination. The authors determined that effective management of soil resources in parks and squares can improve their ability to retain moisture and filter pollutants.

A study by K.R. Castelli *et al.* (2021) demonstrated that increasing biodiversity in urban green spaces can significantly improve their resilience and ecological functions. The authors noted that the use of natural management practices, such as planting native plant species, helps maintain ecosystem stability and increase the number of pollinators and birds. Lastly, following B. Pandey & A. Ghosh (2023), urban ecosystem services are in dynamic interaction with climate change. The study emphasises that competent management of green spaces can mitigate climate risks, minimise the heat island effect and increase the resilience of urban areas.

Thus, research by various authors confirms the important role of urban green spaces in improving the microclimate, reducing air pollution and increasing the resilience of cities to climate change. The study aimed to assess the impact of urban green spaces on improving air quality, regulating microclimate and increasing the resilience of urbanised areas to environmental and climatic challenges.

Materials and Methods

The study was conducted in 2024 (March-August) in the five largest cities of Albania: Tirana, Durres, Shkodër, Vlora and Elbasan. Albania was chosen due to its rapid urbanisation rate, high urban density and significant anthropogenic impact on the environment. These cities differed in their level of urbanisation, green space density and air pollution levels, which were used to assess their impact on air quality, microclimate, ecosystem services and resilience to climate hazards. The climate of the region is Mediterranean, with hot, arid summers, average daily temperatures of +27-35°C and night temperatures of +18-24°C. The average annual precipitation was 800-1,200 mm, with most of it falling in winter (Climate and average..., n.d.). The study compared park areas with a high density of green spaces and densely built-up areas with minimal greenery to identify their impact on the environmental parameters of the urban environment.

The objects of the study were urban green spaces represented by parks, squares, alleys and street trees in Tirana, Durres, Shkoder, Vler and Elbasan. In Tirana, the Great Park, dominated by sycamore, ash and linden trees, and the central areas of the city, where there are no trees, were analysed. In Durres, the city park with Japanese sophora and white acacia, as well as the central areas of the city where there are no trees, were studied. In Škoder, attention was paid to Rosafa Park, where chestnut, beech and oak trees can be found, as well as the industrial area, where there are no trees. In Vlora, the coastline with pine, cypress and seaside pine was analysed, as well as the industrial area, where there are no trees. In Elbasan, the Rinas Park with hornbeam, maple and white willow was studied, as well as industrial areas where there are no trees.

Broadleaved (*Quercus robur* petiole oak, Eastern sycamore *Platanus orientalis*, aspen *Fraxinus excelsior*, *Tilia cordata* linden, *Acer platanoides* maple) and conifers (*Pinus pinaster* pine, *Cupressus sempervirens* cypress, *Pinus pinea*) were analysed. These trees were chosen as they are among the most common and adapted to Albania's climate conditions. Broadleaf and coniferous species, such as scrub oak and loblolly pine, are well adapted to urban environments and perform important ecosystem functions, including improving air quality and regulating temperature. The study was conducted in two types of urban areas: green areas (parks, forest parks, green streets, squares, alleys and street trees) and densely built-up urban areas. The density of trees, their height, trunk diameter and crown area were assessed, which identified their impact on the urban microclimate.

Concentrations of CO_2, NO_2, SO_2, CO, PM2.5, and PM10 were measured during the morning (7:0-09:00), afternoon (12:00-14:00) and evening (18:00-20:00) hours to account for pollution levels during periods of highest activity. Measurements were made using three Aeroqual Series 500 gas analysers manufactured by Aeroqual (New Zealand) and two TSI DustTrak II 8530 aerosol monitors manufactured by TSI (USA). The temperature was recorded with five Fluke 62 MAX infrared thermometers manufactured by Fluke Corporation (USA) and thermal anomalies were detected with a FLIR E6 thermal imaging camera manufactured by FLIR Systems (USA). Humidity was measured using three-channel Hobo U12-011 sensors manufactured by Onset Computer Corporation (USA), installed at heights of 1.5 m, 5 m and 10 m to assess the vertical distribution of humidity.

To assess climate risks, water flow rates, soil erosion and heavy metal (Pb, Cd, Hg) content in soil and water were investigated. Soil moisture sensors Decagon 5TM manufactured by Decagon Devices (USA) recorded moisture retention and soil displacement was monitored using Trimble R1 GPS markers manufactured by Trimble Inc. (USA). Soil samples were analysed in the laboratory using Atomic Absorption Spectrometry (AAS) to determine heavy metal content. Soil contamination with heavy metals was analysed by atomic absorption spectrometry (AAS) on a PerkinElmer AAnalyst 400 instrument manufactured by PerkinElmer (USA) with an accuracy of 0.01 mg/kg (Martin & Wiese, 1996). Biodiversity was assessed by visual observation and recording of bird, insect pollinator and small mammal species. Binoculars Nikon Monarch 5, manufactured by Nikon Corporation (Japan), and automatic photo traps Browning Spec Ops Edge, manufactured by Browning (USA), installed in park areas were used for analyses. Statistical processing of data

Data were analysed in SPSS 26 and Statistica 12. Analysis of variance (ANOVA) was used to identify differences between urbanised and green areas. Pearson's method was used to assess the relationship between green space density and air quality, and linear regression analysis was used to analyse temperature trends (Probability and statistics..., n.d.). Data were presented as mean values with standard errors (± SE).

Results

Impact of urban green spaces on air quality. CO_2 measurements showed that in central areas of Tirana, such as Boulevar Deshmoret e Kombit, carbon dioxide levels were in the range of 420-450 ppm, 10-15% higher than in the Great Park of Tirana, where the concentration was 380-390 ppm. This was attributed to the photosynthetic activity of trees absorbing carbon dioxide and releasing oxygen. In forested areas, such as Daiti National Park, CO_2 levels were even lower, confirming that dense green spaces effectively reduce the concentration of this pollutant.

In Durres, the difference in CO_2 concentrations between central areas and green areas was also significant. Near Liria Square, CO_2 levels reached 430-460 ppm, while in the City Park of Durres, it decreased to 385-395 ppm, corresponding to a 12% reduction. In Shkodër, where the density of green spaces is higher than in other Albanian cities, CO_2 levels in Rozafa Park were 10-15% lower than in the central part of the city. The concentration of NO_2, one of the most dangerous pollutants, also decreased in areas with green areas (Moskalchuk & Orfanova, 2024). In the centre of Durres, especially near motorways and industrial areas, NO_2 levels reached 30-35 ppb, while in green areas, such as the Durres City Park, concentrations decreased to 18-22 ppb. This 25-40% reduction was attributed to the ability of trees to absorb NO_2 through their leaves and slow down the spread of pollutants in the air.

In Škoder, where large areas are planted with trees, the effect of reducing NO_2 was even more pronounced. In Rosafa Park, the NO_2 concentration was 17-21 ppb, which is 30% lower than in areas with high traffic density. In Tirana, the maximum effect was observed in the vicinity of the Great Park, where dense tree plantations reduced NO_2 levels to 20 ppb, in contrast to the main streets, where the concentration reached 35 ppb. The analysis of PM2.5, which poses the greatest danger to human health, showed a significant reduction in areas with dense greenery. In the industrial areas of Elbasan, especially in the vicinity of metallurgical plants, PM2.5 levels reached 20-25 μg/m³, while in Rinas Park the concentration dropped to 10-12 μg/m³, which is 30-50% lower. In Tirana, the greatest reduction in PM2.5 was observed in parks, where dense tree canopies created a natural filter that trapped polluted particles. Additionally, trees were found to influence the composition of the air by increasing the concentration of oxygen during the day and reducing the level of ozone (O_3), which is formed as a result of photochemical reactions (Yerzhanova *et al.*, 2021). In cities such as Vlora, there has been an improvement in the overall air structure, with increased humidity and decreased dust (Table 1).

Table 1. Impact of urban green spaces on air quality

City	Location	Average CO_2 concentration (ppm)	Average NO_2 concentration (ppb)	Average PM2.5 concentration (μg/m3)	Percentage reduction in pollutants
Tirana	Boulevard Deschmoret e Combit	420-450	30-35	20-25	-
	Great Park of Tirana	380-390	18-22	10-12	CO_2 (-10-15%), NO_2 (-25-40%), PM2.5 (-30-50%)
Durres	Liria Square	430-460	32-36	22-26	-
	Durres City Park	385-395	20-23	11-13	CO_2 (-12%), NO_2 (-30%), PM2.5 (-45%)
Shkoder	Central districts	415-440	28-33	18-22	-
	Rosafa Park	375-390	17-21	9-11	CO_2 (-10-15%), NO_2 (-30%), PM2.5 (-40-50%)
Vlora	Industrial zone	425-455	31-34	19-24	-
	Coast	380-400	19-22	10-14	CO_2 (-10-15%), NO_2 (-35%), PM2.5 (-40%)

Table 1, Continued

City	Location	Average CO_2 concentration (ppm)	Average NO_2 concentration (ppb)	Average PM2.5 concentration (μg/m3)	Percentage reduction in pollutants
Elbasan	Industrial district	430-460	33-37	20-25	-
	Rinas Park	385-395	18-21	10-12	CO_2 (-10%), NO_2 (-40%), PM2.5 (-50%)

Source: compiled by the authors

Thus, the results of the study confirmed that urban green spaces in Albania are key in reducing atmospheric pollutants. In areas with high tree density, CO_2, NO_2 and PM2.5 concentrations were significantly lower than in dense city centre areas. The most significant effect was observed in park areas of Tirana, Durres, Shkoder and Vlora, where pollutant levels decreased by 30-50%. This proves the importance of further development of urban green infrastructure in Albania to improve air quality and create a comfortable ecological environment.

Role of trees and parks in reducing temperature and regulating the microclimate. In central areas of Tirana, such as Skanderbeg Square, the average daytime temperature in summer reached 38-40°C, while at night it decreased only to 30-32°C, indicating a significant heat accumulation effect. At the same time, in the Great Park of Tirana, dominated by eastern sycamore (*Platanus orientalis*), ash (*Fraxinus excelsior*) and linden (*Tilia cordata*), the air temperature was 46°C lower during daytime hours and the difference was 35°C at night.

In Durres, where temperatures in the city centre exceeded 36-38°C, temperatures did not rise above 30-32°C in park plantings including Japanese sophora (*Styphnolobium japonicum*) and white acacia (*Robinia pseudoacacacia*). In areas with a high density of green plantings, a significant decrease in soil and asphalt surface temperature was observed, on average by 8-12°C, which was attributable to the effect of shading and reduced solar radiation.

In Shkodër, which had a high density of tree plantations in Rozafa Park, the daytime air temperature during summer months was 6-8°C lower than in industrial and commercial areas. Nighttime temperatures were 4-5°C lower, preventing temperature spikes. The influence of oak (*Quercus robur*), beech (*Fagus sylvatica*) and edible chestnut (*Castanea sativa*) on maintaining the microclimate was particularly notable, as these trees helped to retain moisture and reduce overheating.

In Vlora, especially in coastal areas, trees such as pinia (Pinus pinea), cypress (*Cupressus sempervirens*) and maritime pine (*Pinus pinaster*) reduced air heating by significantly reducing wind speed and evaporation from the soil. The difference between industrial zones and green areas reached 5-7°C during the day and 3-4°C at night.

The analysis of air humidity showed that in city centres, such as Deshmoret e Kombit Boulevard in Tirana, humidity levels were between 35-40%, resulting in discomfort and overheating of the urban environment. In park areas, humidity increased to 50-60%, and in forested areas such as Daithi National Park, it reached 65-70%. In Durres, near the City Park, humidity remained at 55-60%, improving overall thermal comfort.

Wind speed measurements in densely built-up areas showed that it reached 4-5 m/s, contributing to the spread of dust and pollutants. In park areas, especially in areas with dense stands of hornbeam (*Carpinus betulus*) and sharp-leaved maple (*Acer platanoides*), wind speeds were reduced by 20-40%, creating more comfortable conditions. In Shkodër, in areas with a high density of tree plantations, wind speed reduction reached 35%, which reduced air dustiness.

Additionally, the influence of trees on soil and surface temperatures was identified. In paved areas of Tirana, surface temperatures reached 50-55°C during the daytime, while in shaded areas with dense trees, they did not exceed 30-35°C. In Durres, the decrease in surface temperature under trees was 12-15°C, especially in areas dominated by white willows (*Salix alba*), which retain moisture and create additional evaporation (Table 2).

Table 2. Role of trees and parks in reducing temperature and regulating the microclimate

City	Location	Main trees	Average daily temperature (°C)	Average night temperature (°C)	Air moisture (%)	Wind speed (m/s)	Surface temperature (°C)
Tirana	Skanderbeg Square	Lack of trees	38-40	30-32	35-40	3.5-4.5	50-55
	Great Park of Tirana	Sycamore, ash, linden	32-34	26-28	50-60	2.0-2.5	30-35
Durres	City centre	Lack of trees	36-38	28-30	40-45	4.0-5.0	48-52
	Durres City Park	Japanese sophora, white acacia	30-32	25-27	55-60	2.5-3.0	33-37
Shkoder	Central districts	Lack of trees	35-37	27-29	38-42	3.8-4.8	47-50
	Rosafa Park	Chestnut, beech, oak	29-31	24-26	55-65	2.2-2.7	31-34
Vlora	Industrial zone	Lack of trees	37-39	29-31	37-42	4.5-5.5	49-53
	Coast	Pinus, cypress, seaside pine	32-34	26-28	60-65	3.0-3.5	35-38
Elbasan	Industrial district	Lack of trees	38-40	30-32	35-40	4.2-4.8	51-54
	Rinas Park	Hornbeam, maple, white willow	33-35	27-29	55-65	2.5-3.0	32-36

Source: compiled by the authors

Thus, the results showed that in urbanised areas with a high density of green spaces, the air temperature was lower by 4-7°C, the humidity was higher by 15-25%, the wind speed was reduced by 20-40% and surface temperature was reduced by 12-20°C. The greatest effect of microclimate regulation was observed in the parks of Tirana, Durres, Shkoder and Vlora, where broad-leaved trees such as sycamore, ash, chestnut and oak provided the greatest decrease in temperature and increase in humidity. These data confirm the need for increased greening in Albanian cities, especially in high-density areas.

Ecosystem services and their contribution to urban sustainability. In Shkodër, biodiversity indicators reached 92%, due to the high density of green areas, particularly beech (*Fagus sylvatica*), chestnut (*Castanea sativa*) and oak (*Quercus robur*) trees in Rozafa Park. Increased numbers of birds and mammals, including magpies (*Pica pica*), green woodpeckers (*Picus viridis*) and squirrels (*Sciurus vulgaris*) were observed in this area. Air humidity in this area was higher than in the central regions, which also favoured high numbers of insect pollinators, particularly honeybees (*Apis mellifera*).

In Vlora, the level of biodiversity was 88%, due to the combination of urban parks and coastal woodlands represented by pine (*Pinus pinea*), cypress (*Cupressus sempervirens*) and maritime pine (*Pinus pinaster*). These trees provided a stable nesting environment for seabirds and insects, which increased the overall ecological resilience. In Tirana, biodiversity was estimated at 85%, due to the presence of the Great Park of Tirana and the Daiti National Park, where large green areas with ash (*Fraxinus excelsior*), lime (*Tilia cordata*) and eastern sycamore (*Platanus orientalis*) are preserved. In the park areas of Tirana, there was a 30% increase in the number of songbirds over the last ten years. In Durres, biodiversity was lower (78%), due to dense buildings and limited green spaces. Sophora japonicum (*Styphnolobium japonicum*) and white acacia (*Robinia pseudoacacia*) dominated the city's parks, but their impact on maintaining high numbers of animals and birds remained limited. In Elbasan, biodiversity was estimated at 75%, which was attributed to insufficient park space and high industrial pressure.

Air quality had the highest values in Shkodër (90%), which was attributed to the high density of forested areas and less industrial pollution. In areas with high tree density, PM2.5 concentrations were 50% lower, which contributed to a 10-15% reduction in respiratory diseases. In Tirana, the figure was 80%, and the reduction of PM2.5 in green areas was as high as 40%, especially in areas where tree species with a high capacity to absorb pollutants, such as hornbeam (*Carpinus betulus*), sharp-leaved maple (*Acer platanoides*) and linden (*Tilia cordata*), were used. In Durres and Vlora, air quality was rated at 72% and 85%, respectively, indicating a significant influence of coastal winds and greenery in cleaning the atmosphere. In Elbasan, despite the presence of Rinas Park, air quality remained at 70%, which was attributed to high industrial activity (Fig. 1).

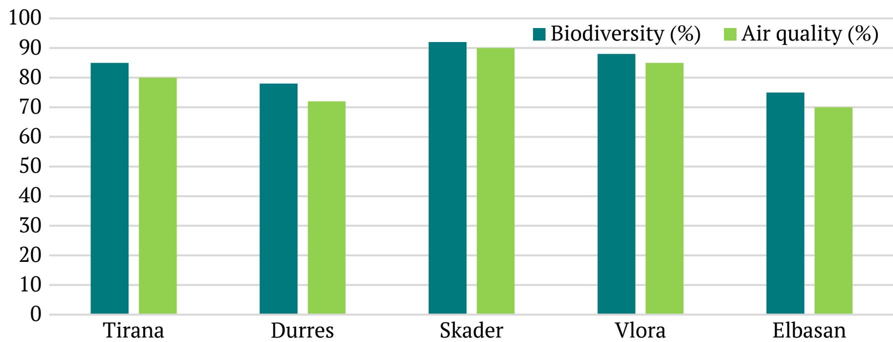

Figure 1. Ecosystem services and their contribution to urban sustainability
Source: compiled by the authors

Thus, cities with extensive green spaces demonstrated higher biodiversity and better air quality. Skader and Vlora were the most environmentally sustainable, while Elbasan and Durres needed to expand their green areas. Despite the dense development, Tirana maintained good performance thanks to its developed park system.

Impact of green spaces on ecosystem services. In the urbanised areas of Tirana, Durres, Shkodër, Vlora and Elbasan, green spaces have had a significant impact on ecosystem services, such as increased humidity and reduced pollution. For example, in areas with a high density of trees, such as the Great Park of Tirana and Rosafa Park in Škodër, there was a 10-20% increase in humidity, which reduced heat stress in the population. These areas also recorded a decrease in air pollution, including NO_2, PM2.5, and CO, as evidenced by a 30-50% reduction in pollution levels in parks such as the Great Tirana Park and Rosafa Park.

Green spaces also helped to improve the water balance (Lipińska *et al.*, 2023). In Tirana and Durres, where flooding was frequent due to poor water absorption of asphalt surfaces, green areas reduced the rate of rainwater runoff by 40%, which reduced the load on drainage systems. Vlora's coastal forests, with their root systems of trees such as sycamore and oak, retained soil and reduced erosion. In Elbasan, analysis of soil samples demonstrated a 15-25% reduction in heavy metals (lead, cadmium, mercury) in the vicinity of green spaces. In areas with a high concentration of linden, maple and hornbeam trees, the highest absorption of toxic substances was recorded, which contributed to the improvement of soil and water quality. Green spaces also mitigated wind speeds, which helped reduce the spread of pollutants and dust (Kunakh *et al.*, 2021). In Tirana, the wind speed in the park was half that of the central areas, which also contributed to the microclimate.

In addition, areas with a high tree density experienced a reduction in the impact of drought (Romanchuck *et al.*, 2017). For example, in Tirana, Durres and Škodër, the soil surface temperature under the tree canopy was 10-15°C lower than in open areas, which helped to retain moisture and reduce evaporation. In Elbasan's Forest parks, soil moisture levels were 20% higher than in areas without greenery (Fig. 2).

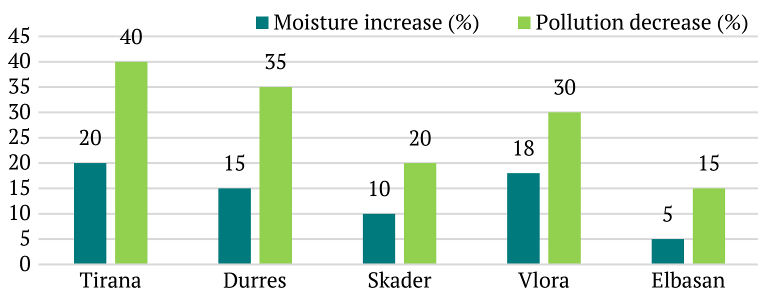

Figure 2. Countering climate change and environmental threats
Source: compiled by the authors

The study confirmed that green spaces in Albanian cities substantially reduce the risks associated with extreme climate events and improve air and soil quality. In areas with a high density of green spaces, there was a marked improvement in the microclimate, a reduction in air and soil pollution, and a significant increase in humidity. Green spaces also effectively reduced the risk of flooding, improved soil water retention capacity and reduced dust, contributing to the environmental sustainability of the urban environment.

Discussion

The results of the study confirmed that urban green spaces have a significant impact on improving air quality, reducing temperatures and increasing the sustainability of urbanised areas Temperature analysis showed that air temperatures in parks and forested areas were 4-7°C lower than in densely built-up areas, proving their role in mitigating the urban heat island effect. An analysis of hydrological characteristics showed that green areas retained up to 40% of precipitation, reducing the load on the city's drainage system and preventing flooding.

As noted by A. Zanzi *et al.* (2021) and H. Pretzsch *et al.* (2023), urban green spaces are key to improving air quality and sustainable management of urban areas. A. Zanzi *et al.* emphasised that integrating agroforestry systems into urban renewal projects can significantly enhance ecosystem services, especially in reducing air pollution and enhancing biodiversity. However, in contrast to their approach, this study focuses on existing green spaces without additional implementation of agroforestry practices. H. Pretzsch *et al.* emphasised the importance of tree age structure, highlighting those older trees absorb more carbon and release more oxygen, which directly affects air quality. This aspect was not addressed in this study, but the findings confirm the importance of trees in microclimate regulation.

According to F. Zhang & H. Qian (2024) and P. Pereira *et al.* (2023), green areas contribute to the reduction of air temperature and the formation of a comfortable urban microclimate. F. Zhang & H. Qian presented a comprehensive review that discusses the mechanisms of the cooling effect of green areas, including evaporative cooling and shading. P. Pereira *et al.* emphasised the balance of ecosystem services and de-services, indicating that if poorly managed, green spaces can become sources of allergens and promote pest breeding. This study did not address such aspects, but its results confirm that the wise placement of green spaces has a predominantly positive effect.

As shown by T. McPhearson *et al.* (2022) and J.A. Belaire *et al.* (2022), the interaction of social, environmental and technological factors is crucial to the effectiveness of urban green spaces. T. McPhearson *et al.* proposed a systems approach to green infrastructure management, emphasising that ecosystem services are most effective when urban design, social structure and technical solutions are accounted for in an integrated manner. This study emphasised the biophysical parameters of green spaces, but the trends identified confirm the importance of integrating them into urban planning. J.A. Belaire *et al.* revealed that detailed biodiversity monitoring can improve the management of urban green spaces. In this study, a 15-25% reduction in Pb, Cd and Hg was recorded, demonstrating the significant potential of green spaces to clean up the environment, coinciding with their findings on the need to control urban ecosystem quality.

As noted by H.L. Reynolds *et al.* (2022) and N. Wessels *et al.* (2021), urban green infrastructure is key to improving the sustainability of urbanised areas, but its effectiveness depends on sound management and community engagement. H.L. Reynolds *et al.* suggested that morphological and functional characteristics of green spaces should be considered to maximise their ecosystem services. This study also confirms that urban green spaces significantly reduce air pollution and regulate microclimate, but it did not analyse in detail the morphological characteristics of trees. N. Wessels *et al.* emphasised that the public's perception of green spaces affects their conservation and development. In contrast to this study, the present research emphasises the biophysical parameters of green spaces, but further research could address the social aspect of their use.

According to W.G. Nissim *et al.* (2023) and S. Tapsuwan *et al.* (2021), green spaces not only fulfil a climatic and aesthetic function but also have a significant role in cleaning the environment. W.G. Nissim *et al.* emphasise the phytoremediation ability of plants, indicating that certain species can effectively absorb heavy metals and pollutants. S. Tapsuwan *et al.* assess the economic value of urban forests and open spaces, emphasising their contribution to reducing heat stress and improving human well-being. These results show a similar effect of reducing temperature by 47°C, confirming the importance of green spaces in mitigating the urban heat island effect.

As shown by Y. Cheng *et al.* (2021) and J.G. Vargas-Hernández *et al.* (2023) climate change requires the adaptation of urban green spaces and their integration into overall sustainable development strategies. Y. Cheng *et al.* analysed the efforts of US municipalities to adapt parks and recreational areas to climate change, identifying the need for long-term planning and sustainable management of green infrastructure. This study also confirms that green spaces contribute to moisture retention and temperature reduction, but aspects of green space management and adaptation to changing climatic conditions require further study. J.G. Vargas-Hernández *et al.* considered urban green spaces as an integral part of the ecosystem, emphasising their role in conserving biodiversity and restoring natural processes. These results are consistent with this conclusion, as significant improvements in soil quality and reductions in pollutants in green spaces have been recorded.

As shown by E. Sevianu *et al.* (2021) and J. Bush *et al.* (2021), the integration of ecosystem services into urban planning is an important tool for improving urban resilience. E. Sevianu *et al.* review the experience of establishing forest parks in Eastern Europe and emphasise that peripheral forests can significantly improve air quality and provide protection against climate threats. This study also identified a 30-50% reduction in NO_2 and PM2.5 concentrations in greened areas, confirming their effectiveness in filtering pollutants. In contrast to their study, this research analyses focus on existing urban plantations rather than peripheral forests. J. Bush *et al.* proposed a methodology for integrating green infrastructure into the urban landscape, emphasising its role in reducing temperature. These results support this effect by recording a 4-7°C temperature reduction in parklands, but in contrast to their study, urban planning tools for the implementation of green infrastructure were not analysed.

According to D.G. Vidal *et al.* (2022) and V. Krivtsov *et al.* (2022), the ecosystem services of urban green spaces can be disaggregated and categorised for better management. D.G. Vidal *et al.* propose a typology of green spaces based on their potential to provide ecosystem services, which allows the identification of optimal measures for the care and development of green spaces. This study focused on the actual impact of plantations on air quality and microclimate, without a detailed classification of their functionality. V. Krivtsov *et al.* analysed the ecosystem services provided by urban ponds and green spaces, emphasising their role in regulating water balance and improving biodiversity. These results support this conclusion, as retention of 20-40% of precipitation in green areas was recorded, but ponds as an element of the urban ecosystem were not addressed.

As noted by L.P. Hopkins *et al.* (2022) and C. Caprioli *et al.* (2021), strategic urban greening requires a multifactorial approach that incorporates both climatic and social aspects. L.P. Hopkins *et al.* proposed a framework model for greening vulnerable neighbourhoods based on community involvement and the use of sustainable tree species. This study confirms the importance of trees for improving air quality and reducing temperature stress, but it did not analyse the social aspects of green infrastructure implementation. C. Caprioli *et al.* considered the transition from grey to green infrastructure as a multilevel process that affects the quality of the urban environment. Evidence on the reduction of soil and air pollution supports this conclusion, but the difference is that this study focuses on the biophysical parameters of green spaces rather than on the processes of their integration into urban development.

As F. Aimar & K. Xhexhi (2024) highlighted, strategic urban greening requires a multifactorial approach that should consider both climatic and social factors. In this study, the authors proposed an analysis of the urban problems of Tirana with a focus on the use of sustainable tree species and eco-villages to improve the microclimate and combat the heat island effect. This study confirms the importance of trees in improving air quality and reducing heat stress but does not include an analysis of the social aspects of green infrastructure. The results on the reduction of soil and air pollution support this conclusion, but the study focuses on the biophysical characteristics of green spaces rather than on the process of their integration into urban development. Thus, the results of this study are generally consistent with the findings of other authors, confirming the role of urban green spaces in improving air quality, reducing temperatures and retaining rainfall. The difference lies in the focus on the actual impact of existing green spaces, whereas many authors consider the strategic management, planning and integration of new green solutions.

Conclusions

The data analysis showed that areas with high density of green areas have a noticeable ability to reduce the level of atmospheric pollutants, especially NO_2 and PM2.5, which confirms their efficiency in capturing harmful particles and gases. Trees and shrubs in urban areas act as a natural filter, absorbing pollutants, reducing the concentration of particulate matter in the air and contributing to the improvement of the ecological background. This is especially important in densely populated urban areas where air pollution levels often exceed permissible standards. In addition, temperature measurements have shown that green spaces significantly mitigate overheating of the urban environment, especially during the summer months. Vegetation has been found to reduce the absorption of solar radiation by hard surfaces such as asphalt and concrete, creating a natural cooling effect. This helps to reduce temperature extremes in cities and increases the comfort of urban environments, especially during periods of extreme heat. In areas with a high density of green spaces, the difference in temperature between open and shaded areas was pronounced, indicating the importance of the shading effect of trees in combating overheating in urbanised areas. The study also confirmed that soils in green areas have an improved ability to absorb and process pollutants including heavy metals (Pb, Cd, Hg). This indicates the important role of green spaces in reducing toxic elements in urban environments and improving soil quality. In addition, green spaces actively contribute to the retention of significant amounts of precipitation, reducing the load on drainage systems. Their ability to absorb moisture and slow its outflow prevents the formation of storm flows, minimising the risk of localised flooding.

Prospects for further research may include a more detailed assessment of the impact of different tree species on pollutant filtration, analysis of social perceptions of green spaces, and development of strategies for integrating nature-based solutions into urban development.

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Conflict of Interest

None.

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Роль міських зелених насаджень і деревних насаджень у покращенні екосистемних послуг і стійкості міст

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Анотація. Метою дослідження була кількісна оцінка впливу міських зелених насаджень на якість повітря, мікроклімат та кліматичну стійкість міст. У дослідженні проаналізовано вплив міських зелених насаджень на якість повітря, регулювання мікроклімату та підвищення стійкості міських територій до кліматичних загроз. У статті було проведено комплексний аналіз існуючих зелених зон у п'яти найбільших містах Албанії: Тирані, Дурресі, Шкодері, Влорі та Ельбасані. Для оцінки екосистемних послуг зелених зон були проаналізовані вимірювання концентрації забруднюючих речовин (CO_2, NO_2, SO_2, CO, PM2.5, PM10), температури, вологості, а також склад ґрунту та його здатність утримувати забруднюючі речовини. Результати показали, що в зонах з високою щільністю зелених насаджень концентрації NO_2 та PM2.5 були знижені на 30-50 %, що свідчить про значну здатність дерев до фільтрації повітря. Вимірювання температури показали, що паркові зони мають на 4-7 °C нижчу температуру, ніж щільно забудовані райони, що підтверджує їхню роль у пом'якшенні ефекту міського теплового острова. Крім того, аналіз ґрунту показав зниження вмісту Pb, Cd і Hg на 15-25 %, що свідчить про здатність зелених зон до природного очищення навколишнього середовища. Зелені зони також утримують 20-40 % опадів, зменшуючи ризик підтоплення та збільшуючи водоутримуючу здатність ґрунту. Результати дослідження підкреслили необхідність інтеграції природоорієнтованих рішень у систему міського управління для підвищення стійкості міського середовища. Отримані дані можуть бути використані для розробки рекомендацій щодо сталого міського планування та обґрунтування екологічно орієнтованих підходів до розвитку міських територій

Ключові слова: забруднення атмосфери; фільтрація повітря; природні рішення; ландшафтне планування; захист ґрунтів

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Detection and ecological characteristics of the alien mite *Aculus taihangensis* (Acari: Eriophyoidea) on *Ailanthus altissima* in the Botanical Gardens of Kyiv and Zhytomyr

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Abstract. Originally used for landscaping, the *Ailanthus altissima* (Mill.) Swingle) has become an invasive species requiring biocontrol, with the *Aculus taihangensis* mite as one of its potential agents. Given this, research aimed to determine the species composition of herbivorous mites on *A. altissima* trees in the Botanical Gardens of Kyiv and Zhytomyr and identify the peculiarities of their distribution and development. To achieve this goal, leaf samples were collected from *A. altissima* plants, with further identification of the detected mites according to the methods

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accepted in acarology. As a result of the monitoring, the alien mite *A. taihangensis* of the superfamily Eriophyoidea was detected on *A. altissima* plants for the first time in Ukraine, namely in the Fomin Botanical Garden of the National Academy of Sciences of Ukraine and the Botanical Garden of Polissya National University. It was found that more intensive reproduction of this phytophage occurs on female plant specimens compared to male ones. The mites preferentially colonise and reproduce more intensively on the leaves of the lower part of the crown, where the air humidity is much higher than in the upper part. These data are important for estimating the number of *A. taihangensis* populations to optimise sampling. It was found that the intensity of mite reproduction during the growing season of host plants gradually increases. Thus, the intensity of reproduction of the first generation of mites was low (0.14-0.70 times), while for the next generation of phytophagous mites, this index increased and reached 0.97-1.3. The comparison of morphological measurements of *A. taihangensis* collected in different ecological and geographical zones confirmed the high variability of individual characteristics in the new habitat. Three groups of traits were identified according to the level of variability: high, moderate, and low variability. Results add to the knowledge about the diversity of eriophyoid mites in Ukraine and their impact on *A. altissima*

Keywords: eriophyoid mites; bioagent; invasion; morphological variability; phytophag; tree crown

Introduction

Biological invasions – the invasion of alien species (invasive species) into ecosystems outside their natural ranges – usually occur for three main reasons: self-dispersal of organisms associated with fluctuations in their numbers and climate change; deliberate introduction of economically important ("useful") organisms (plants, fish, birds, mammals) by humans; accidental introduction with ballast water and ship fouling, with agricultural products, with introductions of "useful" organisms, baggage, etc.

One of the invasive and environmentally harmful trees of Heaven is the *Ailanthus altissima*, which was deliberately cultivated in Europe and Ukraine for urban landscaping in the 19th and 20th centuries and was also used as a perspective phytomeliorative species for the reforestation of sandy areas due to its unpretentiousness to soil and ability to withstand arid conditions. J. Kashefi *et al.* (2022) attributed the invasiveness of *A. altissima* to five characteristics: resistance to extreme environmental conditions, production of numerous allelopathic substances, high seed production and viability, clonal reproduction with abundant sprouts after cutting, and limited insect damage. In addition to its negative environmental impact, the plant also harms human health: Its pollen causes sensitisation, allergic rhinitis, and asthma (Werchan *et al.*, 2022). Due to these aspects, *A. altissima* has been included in the EU's "List of Invasive Alien Species of Concern" (European Commission, 2020).

Controlling the spread of *A. altissima* has become necessary in certain areas, including transport corridors, to ensure safety. In addition, measures to manage it are mandatory under EU legislation. However, traditional control methods remain difficult to implement, expensive, and only partially effective. The use of arboricides is also limited due to the environmental risks involved. Thus, large-scale and long-term eradication of ailanthus is usually not economically viable or feasible. Several studies have been conducted to find alternative, more effective, and environmentally friendly strategies for controlling the spread of ailanthus. A multi-tactical approach with an emphasis on classical biological control looks promising. Research on the use of biological agents to suppress *A. altissima* began in 2004 (Stutz, 2020). To this end, several monophages of this plant have been introduced into the United States, namely the weevils *Eucryptorrhynchus brandti* (Haroldi) and *Eucryptorrhynchus chinensis* (Olivier) (Coleoptera: Curculionidae) (Herrick *et al.*, 2011). As noted by T. Ma *et al.* (2022), these closely related mite species can infest up to 80-100% of *A. altissima* leaves in some regions of China, indicating their high damage and potential threat to the plant.

Another promising bioagent is the mite *Aculus taihangensis* (Hong & Xue, 2005), whose natural range is in Southeast Asia. Research and field observations by S. Stutz (2020) have shown that this mite can damage tall ailanthus seedlings, inhibiting the growth and development of young plants. The study by M. Toldi *et al.* (2022) examined the biological characteristics of predatory mites feeding on *A. taihangensis*. In particular, it was found that the species *Euseius stipulatus* (Athias-Henriot, 1960) can reduce the effectiveness of using eriophyoid mites in biological control programs against *A. altissima.* At the same time, the potential of using the pathogen *Verticillium nonalfalfae* (Inderbitzin, 2011), which can cause verticilliosis in several plants, including *A. altissima*, is being actively studied in different countries. At the same time, researchers B. Dauth *et al.* (2022) warn that significant risks of infection of non-target species accompany the use of such pathogens.

According to J.Q. Ding *et al.* (2006), 46 species of herbivorous arthropods, 16 species of fungi, and several viruses, some of which cause significant damage to the plant, have been recorded in the homeland of *A. altissima*. In China, three species of eriophyoid mites have been found and described on *A. altissima*: *Aculops ailanthi* (Lin, Jin & Kuang, 1997), *Aculops taihangensis* (Hong & Xue, 2005), and *Aculus altissimae* (Xue & Hong, 2005). *A. taihangensis* is believed to have been introduced to Europe (de Lillo *et al.*, 2017) and Turkey (Ozman-Sullivan *et al.*, 2023) with the ailanthus seedlings. In Hungary, another mite species, *Aculus mosoniensis* (Ripka & Ersek, 2014), was described as infesting *A. altissima* trees. Based on new morphological and molecular research, *Aculus mosoniensis* and *Aculops taihangensis* are classified as *Aculus* (Keifer, 1959), with the former species being considered a junior synonym of the latter (de Lillo *et al.*, 2022). That is, only the *Aculus taihangensis* mite has been introduced to Europe from China, and its presence has been confirmed in 13 European countries: Albania, Austria, Bulgaria, Croatia, Greece, Italy, Macedonia, Montenegro, Romania, Serbia, Slovenia, France, and Hungary (Ozman-Sullivan *et al.*, 2023).

The above facts indicate active migration of herbivorous mites from the natural range of *A. altissima* to new regions, particularly Europe, which makes it necessary to study their distribution and biological characteristics in the introduced environment.

In light of this, local research in the Botanical Gardens of Ukraine deserves special attention, as it allows the timely detection of new associations between pests and host plants, as well as assessment of potential phytosanitary risks to the local flora. In connection with the identification of potentially dangerous herbivorous mites for *A. altissima* in Europe, the study aimed to investigate the phytosanitary status of this plant in the conditions of the Botanical Gardens of Kyiv and Zhytomyr. The main focus was on collecting and analysing leaves with signs of damage, identifying the detected mites by comparing them with species described in the scientific literature, and establishing the peculiarities of their distribution in the crown tiers. A separate aspect was the study of the impact of tree sex on the dynamics of mite numbers.

Materials and Methods

The study was conducted during the 2021-2023 growing seasons by route surveys of male and female *A. altissima* trees growing side by side in the Fomin Botanical Garden (Kyiv, 50°44' N, 30°50' E) and the Botanical Garden of Polissia National University (Zhytomyr, 50°25' N, 28°69' E). The trees were more than 100 years old, up to 16-20 m high, with a trunk diameter of 0.6-0.7 m. The vegetation period of both sexes began in early May, with flowering occurring simultaneously at the end of June. Monitoring was carried out from May to September twice a month. For the detection of mites, transparent adhesive tape was used according to the method by L. Bondareva *et al.* (2023). The tape was pressed with a finger with the adhesive side to the lower surface of the leaf. Then, the tape with the prints was applied to the slide and separated from the roll with scissors. The location of the mites was marked with a marker. The use of adhesive tape for the study of Eriophyoid allowed us to quickly obtain data not only on the presence of the object but also to identify almost all stages of the pest. To investigate the degree of mite infestation of young leaves on female and male ailanthus plants, 10 leaves from 10 trees were randomly selected in early May in the Fomin Botanical Garden. In the Botanical Garden of Polissya National University, samples were taken from three levels of the crown: lower tier (up to 1.0 m), middle tier (1.1-2.0 m) and upper tier (above 2.1 m). For each level, 5 trees were selected, from which 10 leaves were randomly cut from different branches using garden shears (for the middle and upper tiers). The leaves were placed in paper bags, labelled and transported to the laboratory for further microscopic analysis. In the laboratory, under an Optika B-350 microscope (Country of manufacture – Italy) using a dissecting needle soaked in glycerol, mites were examined at 80x magnification, and the number of leaves with mites, the average number of mites per leaf, including adults and pre-magical stages, were counted. The study was conducted in accordance with the Convention on Biological Diversity (1992).

Eriophyoid mites were stored in 70% ethyl alcohol with 5-6% glycerol. Subsequently, they were placed in Hoyer's medium, without fibres, and then kept on a heating plate for two hours at 50°C. The mites were identified by comparing the external structure of the adults with the descriptions and original drawings given in research by X.-Y. Hong & X.-F. Xue (2005), G. Ripka & L. Érsek (2014), E. de Lillo *et al.* (2022), S.K. Ozman-Sullivan *et al.* (2023). To study the variability of morphological characters of *A. taihangensis*, mite specimens placed in a drop of a mixture of glycerol and sodium hypochlorite solution, which was used to discolour the covers quickly, were used. Morphometric measurements were performed using an eyepiece micrometer. All measurements of mites were performed according to the method proposed by J. Amrine & D. Manson (1996), with dimensions in micrometres (μm). The study analysed 24 protogynous females and 6 males. The reproduction rate of mites is calculated by the formula (Stankevych & Hornovska, 2022):

$$Rr = Na / Nn, \qquad (1)$$

where Rr is the reproduction rate; Na – absolute number of species in this year; Nn – the same indicator in the previous year. The range of normal response of characteristics was determined according to M. Kliuchevych *et al.* (2020):

$$D = a - c, \qquad (2)$$

where *D* – range of normal response; *a* – the maximum (max) value of the parameters of characteristic; *c* – minimum (min) value of the parameters of the characteristic. Microsoft Excel and the "STATISTICA" statistical package were used for data processing and presentation. The studied samples are in the collection of mites of the laboratory of entomology and resistance of crops against pests of the Institute of Plant Protection of the National Academy of Sciences.

Results and Discussion

During regular inspections of *A. altissima* for herbivorous mites in the territory of the Fomin Botanical Garden (Kyiv) and the Botanical Garden of Polissya National University (Zhytomyr), the mite *A. taihangensis* was first detected and studied (Fig. 1).

Figure 1. *Aculus taihangensis*
Source: photo by the authors

Female: Body fusiform, 225-278 long, 57-59 width. Gnathosoma 22, projecting obliquely down. Prodorsal shield 39-42 long; prodorsal shield with frontal lobe, prodorsal shield design with the network. Dorsal tubercles on rear margin, 33 apart, scapular setae (sc) 50 projecting posteriorly. There is a stern line. Coxal area with granules. Dorsal annuli 45-47, with small dot microtubercles on rear annular margins, and ventral annuli 77-79, with small microtubercles on rear annular margins. Female genitalia 11 long, 21 wide coverflap with 8 longitudinal ridges, proximal setae on coxistemum 25 long.

Legs I 45 long, femur 13, basiventral femoral setae 10; genu 7 long, antaxial genual setae 25 long; tibia 12, paraxial tibial setae 5, located near the dorsal base; tarsus 8 long; empodium simple, 5-rayed, solenidion not knobbed.

Legs II 39 long, femur 11, basiventral femoral setae 11; genu 6 long, antaxial genual setae 13 long; tibia 10; tarsus 8 long; empodium simple, 5-rayed, solenidion not knobbed.

Male: 275-180 long, 64-66 width; proximal setae on coxistemum III 20 long.

Since the presence of *A. altissima* has been confirmed in 27 European countries (EPPO, 2024) and the identification of *A. taihangensis* has been confirmed in 13 European countries, it is not surprising that the mite has also been found in Ukraine.

It is known that some researchers have used morphological characters and measurements to identify *A. taihangensis* found in its native environment and individuals introduced to different ecological and geographical zones of Europe and Turkey. Compared them with our data to study the variability of these traits or their reaction rate when the phytophagous is moved to new environmental and geographical conditions. It is known that the reaction rate is the range of adaptation that determines the limits of an organism's variability. It arises under the influence of all environmental factors and is controlled by the organism's genotype.

Table 1 shows the morphometric measurements and quantitative indices of the characteristics of protogynous females of *A. taihangensis* collected by acarologists from different regions of the world, as well as our data. The comparative analysis shows that the variability of mite characteristics used to identify this species found in its native range (China) and those introduced into new ecological and geographical conditions in Hungary, Italy, Turkey, and Ukraine is characterised by a relatively high degree of variability and varies in a fairly wide range.

Table 1. Morphological measurements (μm) of *A. taihangensis* protogyne females

Characters		**Sources**				
		X.-Y. Hong & X.-F. Xue (2005) (China)	**G. Ripka & L. Érsek (2014) (Hungary)**	**E. de Lillo *et al.* (2017) (Italy)**	**S.K. Ozman-Sullivan *et al.* (2023) (Turkey)**	**Personal data (Ukraine)**
Body	length	288	205-330	237-275	242-290	225-278
	width	75	68-78	55-57	56-60	57-59
Prodorsal shield	length	38	40-50	40-45	42-45	39-42
Genital coverflap	length	18	18-23	10-12	10-12	11
	width	25	23-26	21-22	21-22	21
	ridges	8	13-14	10	10	8-9
Body semiannuli	dorsal	51	50-59	45-50	44-46	45-47
	ventral	87	70-83	73-85	71-79	77-79
The number of empodium rays	rays	5	5	5	5	5

Source: compiled by the authors

According to the ability to change the research of characteristics in the new conditions of the mite's existence, several groups were identified: with high, moderately low variability, and stability of development. The characteristics with a high range of reaction norms (more than 70%) include the number of rollers on the genital coverflap and their length parameters. Characteristics with a moderate range of variability (40-69%) include body length and dorsal body semiannuli. Characteristics with a low range of variability (up to 39%) include the rings of the ventral surface of the body, the length of the scutellum, and the width of the genital coverflap. Only one characteristic, the number of empodium rays, is characterised by the stability of its manifestation in all studied mite populations.

Aculus taihangensis overwinters under the outer scales of a bud. In spring, when the leaves blooming, it leaves its wintering places and begins to feed on young leaves. The mites suck plant sap with their mouthparts, causing the leaf margins to curl upwards and turn yellowish. As noted by several authors (Ripka & Érsek, 2014; de Lillo *et al.*, 2017), necrosis, premature leaf fall, and even death of young trees can be observed on heavily infested plants. In our case, no such manifestations were observed. *A. taihangens* is a wandering eriophyoid mite that is openly present on the leaf surface, mainly on the underside, and can form large populations on forage plants. During the years of research, have observed accumulations of eggs, nymphs, and adult mites along the midveins of the lower leaf surface. The study of the *A. taihangensis* population dynamics during the growing season revealed stable development, characterised by two to three generations in Kyiv. It was found that the intensity of mite reproduction during the growing season gradually increases. Thus, for the first generation, the intensity of reproduction was low (0.14-0.70), while for the next generation of the phytophagous mites, this indicator increased and amounted to 0.97-1.3. The number of mites peaked in July and decreased in late August. In September, no mites were found on the leaves.

At the beginning of May, when the active unfolding of leaf blades on female and male trees occurs, studied the mite infestation of ailanthus leaves in the Fomin Botanical Garden. The analysis of the results (Fig. 2) showed that the leaves of female plants were infested much more than those of male plants. During the three years of observations, the degree of colonisation of young leaves on female trees ranged from 10.8 to 11.3%, while for male specimens, this figure was lower and varied from 8.5 to 9.7%. Summarising the data for three years, the average level of *A. taihangensis* mite infestation on female plants was 11.03%, while on male plants, it was 9.1%, indicating a steady trend of higher susceptibility of female plants to infestation.

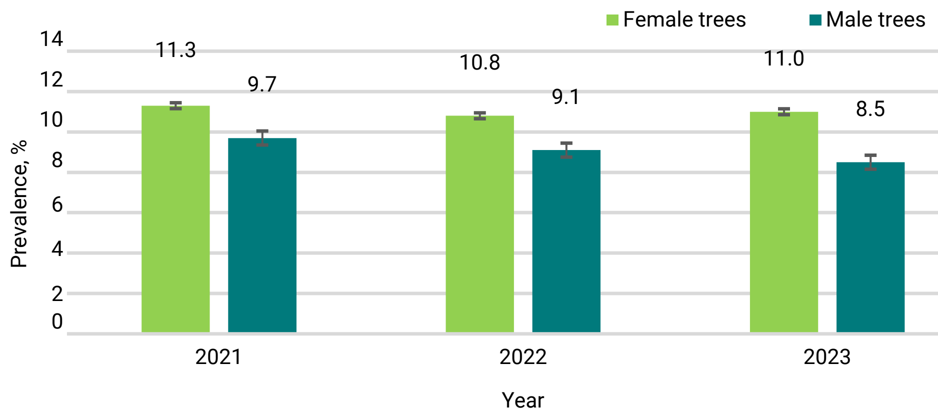

Figure 2. Prevalence of *A. taihangensis* on different sexes of *A. altissima* plants in the academician O.V. Fomin Botanical Garden (2021-2023)

Source: compiled by the authors

Possible differences may be due to both morphological characteristics of the leaf surface and the chemical composition of the leaves, which affect mite behaviour. For a deeper understanding of the mechanisms of differences in mite infestation, further research should include analysis of leaf chemical composition, microstructural characteristics of the epidermis, and environmental factors that may affect the spread of *A. taihangensis*.

In the Botanical Garden of Polissia National University from 2021-2023, the distribution of the mite *A. taihangensis* on different levels of the crown of *A. altissima* was researched. The data analysis (Table 2) showed that the mite infestation of leaves was highest in the lower crown tier, where the average infestation rate was 80.9% over three years. A much smaller number of mites was found in the middle tier (17.7%), and in the upper tier, the infestation was minimal (0.4%). The obtained results indicate a pronounced tendency to colonise the lower branches, which is probably due to more favourable microclimatic conditions, especially high humidity and shading. This confirms the adaptation of *A. taihangensis* to high humidity conditions.

Table 2. *A. taihangensis prevalence* in crown tiers of *A. altissima* in the Botanical Garden of Polissya National University (2021-2023)

Year	Prevalence, %		
	Lower tier	Middle tier	Upper tier
2021	83.7 ± 0.61	16.3 ± 0.56	0.49 ± 0.01
2022	80.6 ± 0.54	19.2 ± 0.64	0.31 ± 0.03
2023	81.8 ± 0.29	17.7 ± 0.54	0.41 ± 0.03
Year	**Prevalence, %**		
	Lower tier	**Middle tier**	**Upper tier**
On average	80.9 ± 0.49	17.7 ± 0.58	0.40 ± 0.02
LSD_{05}	0.5	0.6	0.02

Source: compiled by the authors

X. Han *et al.* (2020) researched the effect of air moisture on the behavior and abundance of *Phyllocoptes maackis* X. Han *et al*. on *Euonymus maackii* Rupr. The authors noted that the number of species was higher on young leaves, which contain more moisture. At the same time, the authors' research showed that mite activity decreased under unfavourable conditions, such as low temperatures or heavy precipitation. Thus, mites are sensitive to changes in the environment, which highlights the importance of studying these factors to understand their environmental impact.

Aculus taihangensis belongs to the superfamily Eriophyoidea, which attracts considerable attention from researchers because it contains aggressive pests of fruit, vegetable, ornamental, and other crops (Yanovskyi *et al.*, 2021; 2022). This superfamily is also intensively studied due to the suitability of some species for controlling the density of herbaceous weeds and invasive plants on agricultural lands and in natural ecotopes (Magud *et al.*, 2007). Due to the narrow specialisation of many eriophyoid mites on certain plant species, they are considered as potential biological control agents capable of regulating populations of undesirable vegetation without harming target crops. This combination of phytosanitary importance and ecological potential makes the superfamily Eriophyoidea one of the key groups in modern acarofauna research.

At the same time, understanding the mechanisms of spread of these mites is equally important, as the ability to disperse effectively determines their ecological plasticity and potential for biological control. According to research by K. Michalska *et al.* (2010), eriophyoid mites are usually spread by air currents, although rain, snow, and phoresis remain less common mechanisms. All but the last of these methods are based on random factors and may be ineffective, especially if the host population density is low or the number of mites capable of migration is small. Vertical transmission can potentially be more effective in ensuring the establishment of new hosts, but this mechanism is not well understood in eriophyoid mites (Chetverikov *et al.*, 2022). In this context, it is important not only to understand how eriophyoid mites spread but also to assess the consequences of their invasion into new ecosystems. This necessitates constant monitoring of the emergence of new species and analysis of their potential for invasion.

The rapid spread of invasive species in the world, including in Ukraine, forces scientists to closely monitor this phenomenon, regularly publish new data on findings, and compile initial species lists. This is aimed at raising awareness of the problem. At the same time, only a small proportion of alien species become invasive. For example, in Europe, out of approximately 12,000 alien species, only 10-15% have been designated as invasive (Sundseth, 2016).

Several species of alien mites and insects have been recorded in Ukraine for the first time (Bondareva & Chumak, 2020). For example, the mite *Pentamerismus oregonensis* (McGregor, 1949). Insects include the moths *Phyllonorycter platani* (Staudinger, 1870), *Phyllonorycter issikii* (Kumata, 1963), *Cameraria ohridella* (Deschka & Dimic 1986), *Parectopa robiniella* (Clemens, 1863) (Matsakh & Kramarets, 2020), *Metcalfa pruinosa* (Say, 1830) (Uzhevskaya *et al*., 2012), *Agrilus planipennis* (Fairmaire, 1888) (Drogvalenko *et al.*, 2019), *Corythucha arcuata* (Say, 1832) (Meshkova *et al.*, 2020), and other species of invasive biota in Ukrainian ecosystems (Babytskiy *et al.*, 2023).

This list demonstrates the increasing frequency of new alien species in Ukraine, which indicates the relevance of continuous monitoring and the need for scientific assessment of their potential impact on local ecosystems. Particular attention is drawn to both mites and insects, which can exert significant pressure on native species and cause disturbances in ecological balance.

When studying the spread of living organisms beyond their natural range, little attention is paid to the causes related to the biological characteristics of the invasive species themselves. There are many reports in the literature that the trigger for invasion can be individual elements or a complex of external conditions (temperature, humidity, climate change towards higher temperatures), a sharp and multifaceted increase in the globalisation of all human activities, etc. S.E. Meyer *et al.* (2021) examined how invasive species responded to natural and human-caused disturbances such as fire, soil disruption, and climate change. The authors highlighted that invasive species often reacted more rapidly than native ones, allowing them to dominate disturbed ecosystems. X. Zhang *et al.* (2022) found that invasive plants showed greater growth than co-occurring native species in live soil subjected to a drought-rewetting cycle. This demonstrated that invasive species had an adaptive advantage under fluctuating climate conditions, which facilitated their further spread.

A. Mosyakin (2009) summarised the main hypotheses of plant invasiveness: escape from "natural enemies", "evolution of invasiveness", "evolution of increased competitiveness", "new weapons", "empty niche", and "species richness" The author notes that the above hypotheses are, in fact, a generalisation of practical data available in modern invasive biology.

However, none of the hypotheses claims to be universal but explains the invasive process in terms of the action of one factor or group of factors. It is emphasised that when developing hypotheses of invasiveness and practical measures to combat phytoparasites, the key role should belong to environmental factors and the trophic component of the biotic environment of phytoparasites. Therefore, the importance of studying the biological characteristics of the invasive species themselves is not emphasised. At the same time, it can be assumed that, together with plants of a certain species, the whole complex or individual trophically related parasites of a given plant species may simultaneously enter new ecological and cenotic conditions. The question of why only certain species survive, and not only survive, but also show the ability to engage in outbreaks of mass reproduction, remains open.

One of the reasons for this phenomenon is escape from "natural enemies", "empty niche", etc. However, other members of the consortium of this invasive plant also find themselves in similar conditions. Thus, in the case of the introduction of *A. altissima* plants, other phytophages and pathogens of this species may enter Europe, Turkey, and the United States (Bielski *et al.*, 2024). For example, the Chinese weevil species *E. brandti* and *E. scrobiculatus*, which naturally damage *A. altissima*, are currently being tested in the United States as potential biological control agents for this species (Herrick *et al.*, 2011; Ma *et al.*, 2022). However, the situation with mites is somewhat different – according to M. Skvarla *et al.* (2021), only a few mite species have been recorded on *A. altissima* in new areas, indicating limited movement of this group of phytophages with the plant.

Agreeing with the entire set of hypotheses of the influence of external factors on the invasiveness of biota in general, assume that this phenomenon is also based on the individual genetic characteristics of a species, which can be expressed by the variability of the organism's characteristics. The natural laws of the functioning of the triad 'genome – characteristics – environment' are generally not sufficiently studied and are not taken into account when studying the phenomenon of biota invasiveness.

Conclusions

Research is an important step forward in studying the eriophyoid mites of Ukraine associated with such a highly invasive species as *A. altissima*. The presence of the alien *A. taihangensis* in Kyiv and Zhytomyr is a new record for the fauna of Ukraine. Comparison of morphological measurements of *A. taihangensis* collected in different ecological and geographical zones allowed us to identify traits with high, moderate, and low variability and one stable trait – the number of empodium rays. It was found that *A. taihangensis* is a polycyclic species capable of developing two or three generations during the growing season. The population size reaches its peak in July and sharply decreases by September. The predominant colonisation of the lower tier of the tree crown by mites was found. Thus, the level of leaf mite infestation in the lower tier of the crown for three years was 80.9%, in the middle tier, the population was much lower, 17.7%, while in the upper tier it reached only 0.4%, indicating a clear vertical differentiation in the distribution of mites, which is explained by favourable microclimatic conditions, in particular, high humidity and shading. The influence of the sex of *A. altissima* plants on the level of mite infestation was noted: female individuals were more infested than male ones. The average level of *A. taihangensis* mite infestation on female plants was 11.03%, while on male plants it was 9.1%. The results of our observations suggest that *A. taihangensis* does not perform a significant function as an effective biological agent for controlling the population of *A. altissima*. This is because the level of damage to the leaf surface of trees was insignificant: the damage did not have a significant impact on the physiological state of adult trees growing in the territory of the Botanical Gardens in Kyiv and Zhytomyr. In this regard, there is a need for further, larger-scale research to clarify the natural distribution of *A. taihangensis* throughout Ukraine. It is also important to collect additional data on its biology, ecological preferences, and potential impact on different age groups of *A. altissima* in open natural ecosystems.

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Conflict of Interest

None.

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Виявлення та екологічна характеристика чужорідного кліща *Aculus taihangensis* (Acari: Eriophyoidea) на айланті найвищому (*Ailanthus altissima*) в ботанічних садах Києва та Житомира

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Анотація. Спочатку використаний для озеленення, айлант найвищий (*Ailanthus altissima* (Mill.) Swingle)) став інвазійним видом, що потребує біоконтролю, одним із потенційних агентів якого є кліщ *Aculus taihangensis*. З огляду на це, дослідження було спрямоване на визначення видового складу рослиноїдних кліщів на деревах *A. altissima* в ботанічних садах Києва та Житомира, виявлення особливостей його поширення та розвитку. Для досягнення цієї мети було проведено збір зразків листя з рослин айланта з подальшою ідентифікацією виявлених кліщів згідно з прийнятими в акарології методами. В результаті проведеного моніторингу вперше на території України, а саме в Ботанічному саду ім. академіка О. В. Фоміна Національнї академії наук України та Ботанічному саду Поліського національного університету, на рослинах *A. altissima* виявлено чужорідного кліща *A. taihangensis* надродини Eriophyoidea. Встановлено, що більш інтенсивне розмноження цього фітофага відбувається на жіночих екземплярах рослин у порівнянні з чоловічими. Кліщі переважно заселяють та інтенсивніше розмножуються на листках нижньої частини крони, де вологість повітря значно вища, ніж у верхній частині. Ці дані важливі для оцінювання чисельності популяцій *A. taihangensis* з метою оптимізації вибірки. Встановлено, що інтенсивність розмноження кліщів протягом вегетаційного періоду рослин-живителів поступово зростає. Інтенсивність розмноження першого покоління кліща була низькою

(0,14-0,70 раз), тоді як для наступного покоління фітофага цей показник збільшився і сягав 0,97-1,3. Проведене порівняння морфологічних вимірів *A. taihangensis*, зібраних у різних еколого-географічних зонах, підтвердило високу варіабельність окремих характеристик у нових умовах існування. Виділено три групи ознак за рівнем мінливості: з високою, помірною та низькою варіабельністю. Отримані результати доповнюють знання про різноманітність еріофіоїдних кліщів в Україні та їх вплив на *A. altissima*

Ключові слова: еріофіоїдні кліщі; біоагент; інвазія; морфологічна варіабельність; фітофаг; крона дерева

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Degradation and restoration of forest ecosystems in the context of war: Environmental and economic challenges to Ukrainian national security

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Abstract. The study aimed to identify the effects of military operations on forest ecosystems and find effective approaches to their restoration in the face of environmental and economic

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challenges. The methodology used was to analyse the impact of military operations on forest ecosystems, assess the economic consequences of forest degradation, and develop a restoration strategy through demining, reclamation and the implementation of monitoring systems. The study analysed the extent of destruction of forest ecosystems as a result of the war, including loss of tree cover, damage caused by fires, mining and mechanical damage. The study established that most forest areas have lost their ability to regenerate themselves due to changes in the hydrological regime and biodiversity. The data on soil contamination with heavy metals are summarised: lead 450 mg/kg and cadmium 6.5 mg/kg were detected in Izium forest; lead 390 mg/kg and cadmium 5.2 mg/kg in Sviatohirsk forest; lead 280 mg/kg and cadmium 3.8 mg/kg in Chernihiv forest; lead 320 mg/kg and cadmium 4.1 mg/kg in Kherson forest. The economic losses from the decline in forest resources, reduction in forest industry revenues and job losses were estimated. The impact on agriculture was analysed, including a decrease in soil productivity, erosion and changes in microclimate. Social consequences, including population displacement and increased unemployment, were identified. Threats to national security due to environmental destabilisation were outlined. The necessity of an integrated approach to restoration, including demining, soil treatment, reforestation with adaptive species and satellite monitoring to prevent illegal logging, was substantiated. The findings of this study can be used to develop strategies for restoring forest ecosystems, planning environmental policy, as well as to attract international assistance and implement sustainable forestry practices in Ukraine

Keywords: soil contamination; mining; biodiversity; phytoremediation; state policy

Introduction

Ukrainian forest ecosystems perform important functions for maintaining ecological balance, supporting biodiversity, regulating climate conditions and ensuring economic stability. However, the ongoing war in the country is having a devastating impact on these natural systems. As a result of the hostilities, the area of forests has significantly decreased, soil and water pollution are increasing, and the ability of ecosystems to recover is deteriorating. Physical destruction of trees, fires, mining, and negative impacts on flora and fauna have become some of the main consequences of military conflicts. This process not only threatens natural resources but also creates serious economic challenges. Restoration of forest ecosystems in the wake of war requires new approaches and strategies that combine environmental initiatives with economic sustainability.

The problem of degradation of forest ecosystems during military conflicts is a relevant topic for research, as war significantly affects the state of natural resources, including forests. Z. Krajnović & A. Smolek (2024) noted that the war caused serious destruction of forests due to hostilities, including artillery shelling and air strikes. The study also emphasised the importance of establishing a monitoring system for rapid response to forest fires. A.B. Tarnavskyi & V.V. Rykhva (2024) highlighted the significant pollution of soil and water in the Donetsk region as a result of hostilities. This has severely complicated the restoration of ecosystems, as toxic substances have greatly reduced the natural ability to self-healing. S. Löfqvist *et al.* (2022) highlighted the need for a comprehensive approach to forest restoration, including environmental, social and economic factors. The role of international assistance in the implementation of restoration programmes was particularly emphasised. J. Castro *et al.* (2021) noted that military operations contributed to the growth of illegal deforestation due to the lack of control in the conflict zone. To address this issue, the study proposed an enhanced system of monitoring and punishment for violations. R.Y. Zakari *et al.* (2024) emphasised the importance of introducing modern forest monitoring technologies, in particular satellite systems, to detect violations and pollution. The need to respond to illegal logging was noted.

A.K. Priya *et al.* (2023) proposed the use of phytoremediation to clean up soils after they were contaminated as a result of military operations. This method restored environmental conditions in areas affected by toxic substances. T.T. Nguyen *et al.* (2023) noted that climate change, exacerbated by the war, has a negative impact on forest restoration. Extreme weather events complicate the stability of forest ecosystems and their ability to recover. A.M. Tedesco *et al.* (2022) emphasised the importance of international cooperation and funding for the restoration of forest ecosystems. The study proposed the creation of financing mechanisms through green bonds and environmental funds to support restoration activities. R.L. Chazdon *et al.* (2020) emphasised the importance of local communities in the process of forest restoration, as it helps not only to restore ecosystems but also to strengthen social resilience at the local level. F. Hua *et al.* (2022) noted that for forest restoration, it was necessary to adapt new approaches to forestry that combine environmental and economic interests. The development of incentive systems for the sustainable use of forest resources was emphasised.

Despite significant advances in research on the effects of war on forest ecosystems, some gaps require further study. In particular, the long-term economic impact of the loss of forest resources on local economies, as well as the effectiveness of phytoremediation and other soil remediation methods, remain understudied. The impact of climate change, exacerbated by military operations, on forest ecosystems needs to be investigated in more detail and effective adaptation strategies need to be identified.

The study aimed to analyse the impact of the war on Ukraine's forest ecosystems and develop possible ways to restore them, as well as to examine the environmental and economic challenges facing the country. The objectives of the study were to examine the extent of physical destruction of Ukraine's forest ecosystems as a result of hostilities, including landmines, artillery shelling, air strikes and fires, and to assess the economic impact of forest degradation, including loss of forest resources, reduced agricultural productivity and impact on tourism and recreational potential. The study also included consideration of strategic approaches to restoring forest ecosystems, including demining, land reclamation, reforestation, establishing an environmental monitoring system and attracting international support.

Materials and Methods

The analysis covered the territories of Ukraine affected by the war, in particular Donetsk, Luhansk, Kharkiv, Zhytomyr, Dnipro, Zaporizhzhia, Kherson, Chernihiv and Sumy regions. The study considered the period from 2020 to 2024 and analysed the situation for 2028 as a post-war period, which is important for interpreting forecasts of forest resource recovery and economic impacts. For this purpose, a forecasting method was used based on current trends in ecosystem degradation, which assessed the probable changes in the ecological and economic state of the territories after the end of the war.

The study examined several sources and initiatives that contribute to the restoration and conservation of forest ecosystems, as well as monitoring their condition. In particular, the study analysed the activities of the State Environmental Inspectorate of Ukraine (2025), which monitors compliance with environmental standards in the forest sector and performs the functions of identifying violations and taking appropriate measures to eliminate them. The role of the State Agency of Forest Resources of Ukraine (2024), which coordinates and manages the national forest resources, organising measures for sustainable use and restoration of forests, was also considered. An important element of the study was the audit report on forestry and hunting (Accounting Chamber, 2024), which is used for assessing the effectiveness of forest management, identifying problems and providing recommendations for their solution. In addition, the United Nations Decade on Ecosystem Restoration (2021-2030) (2019), which provides financial and technical assistance for the restoration of natural ecosystems, including forests affected by environmental disasters, was analysed. The article also examined the activities of the Global Environment Facility (2024) as a source of funding for international environmental projects, including forest restoration and climate change. The Regulation (EU) 2024/1991 of the European Parliament and of the Council "On Nature Restoration" (2024), which implements ecosystem restoration projects on a global scale, was also considered separately. Particular attention was paid to the methodology of satellite forest monitoring using Sentinel-2A/B satellite data (Mozghovyi *et al.*, 2024), which can be used for the efficient detection of illegal logging and changes in forest cover. Volunteer initiatives are also analysed, including the Million Trees for Ukraine project (The "Million Trees..., 2020), which brings together various organisations to plant trees on a massive scale in the areas of Ukraine affected by environmental disasters. In addition, the effectiveness of the FOREST RECOVERY project (Forest of Ukraine, 2023), which aims to restore forest ecosystems in contaminated areas and bring them out of critical condition through reforestation, soil treatment, and the use of phytoremediation technologies, is investigated. The report by Kyiv School of Economics (2024) was an important source of information

To study the impact of artillery shelling, air strikes, land mines and forest fires on ecosystems, a method of integrated environmental analysis was applied, including analysis of drone photography and satellite monitoring data. This assessed the extent of forest damage, classified types of degradation and pollution, including explosions, soil and water contamination with toxic substances, and assessed illegal logging. The analysis covered the Izium forest (Kharkiv oblast), Sviatohirsk National Park (Donetsk oblast), forests around Chernihiv and forests near Kherson (after the flood). This approach identified the main factors of forest ecosystem degradation and problems related to the weakening of environmental protection structures during the war.

Risk analysis assessed the environmental threats arising from the degradation of forest ecosystems. This method determined the impact of the decline in forest cover on water and air pollution, as well as on public health. In addition, threats to social stability were assessed, including forced resettlement of people due to the destruction of natural areas and environmental pollution. Economic analysis was used to develop a strategy for the restoration of forest ecosystems, including research into international financial initiatives such as UN, EU and World Bank programmes. In addition, this method addressed the need to introduce environmental insurance instruments for forestry enterprises, as well as to create economic mechanisms to support the restoration process.

Results

Impact of hostilities on forest ecosystems. Forest ecosystems are key in maintaining ecological balance, conserving biodiversity, regulating climate and meeting the economic needs of society. They are not only a source of timber, but also a natural barrier against soil erosion and a habitat for many species of animals and plants. However, during military conflicts, forests become one of the most vulnerable natural areas. Military actions cause significant damage to forest ecosystems, which is manifested in their physical destruction and contamination with toxic substances such as lead, uranium, fuel residues, chemical compounds contained in ammunition, as well as combustion and explosion products. Other major negative factors include large-scale fires, mining, artillery shelling, air strikes, and uncontrolled use of natural resources, including illegal deforestation and disturbance of the natural landscape. The peculiarity of the war's impact on forests is that the consequences of the destruction can last for decades. Even after the end of hostilities, areas remain dangerous due to mining, pollution and disruption of the natural balance. In addition, during periods of instability, the risk of illegal deforestation increases, which only deepens the environmental crisis. According to the State Ecological Inspectorate of Ukraine (2025), in 2024, 2.4 thousand cases of illegal logging (16.1 thousand cubic metres) were detected, with the highest rates in Zhytomyr (39.8%), Kharkiv (12.2%) and Dnipro (8.0%) regions. More than 80,000 km² of Ukraine's territory is contaminated with mines and ammunition. The problem is especially acute in Donbas, Luhansk, Kharkiv and southern regions of Ukraine, where weakened control over forests is accompanied by an increase in demand for timber. Table 1 shows the main quantitative indicators of the physical destruction of forest ecosystems as a result of the war.

Table 1. Physical destruction of forests as a result of the war in Ukraine (2020-2028)

Metric	2020 (before the war)	2024 (during the war)	2028 (after the war) forecast
The total area of forests affected by the war	0 million ha	3.5 million ha	2.0 million ha
Area of forests destroyed by fires	0 km² (0 ha)	1,150 km² (115,000 ha)	30,000 km² (3,000,000 ha)
Area of forest fires	0 km² (0 ha)	320 thousand ha	50,000 km² (5,000,000 ha)
Forests contaminated with mines and ammunition	0 km² (0 ha)	450 thousand ha	50,000 km² (5,000,000 ha)
Forests affected by artillery shelling and explosions	0 km² (0 ha)	more than 160 thousand ha	30,000 km² (3,000,000 ha)
Biodiversity loss as a result of war	none	significant decline in populations of rare species	gradual recovery of biodiversity, but several species may remain under threat
Damage to forestry infrastructure	0 objects	more than 120 forest roads and facilities	10-20% of restored facilities
Total number of forest areas where restoration will take time	0 ha	more than 2.2 million ha	1.5 million ha

Source: compiled by the authors based on Kyiv School of Economics (2024)

The indicators reflect the damage to Ukraine's forest ecosystems as a result of the war. They cover the total area of forests affected by hostilities, as well as areas destroyed by fires and contaminated by mines and ammunition. In addition, data is provided on forest areas damaged by artillery shelling and explosions. The report also highlights the serious consequences for biodiversity, forestry infrastructure and the need to restore large areas of forests where the recovery process will take a long time.

The war has caused major losses for forests located in eastern and southern Ukraine, where active hostilities are taking place. The forests in the immediate combat zone suffered the greatest losses. Artillery shelling, fires and mines were the main factors that led to the destruction of forests. In regions such as Donetsk, Luhansk and Zaporizhzhia, large areas of forests were not only damaged but also made dangerous for recovery due to mining (Barker *et al.*, 2020). This seriously hampers the natural recovery of forest ecosystems in these areas. Destroyed forests often lose their fertile soil layer, which is the basis for the further growth of new plants. Environmental pollution and tree damage also significantly slow down the recovery process. Restoration of such areas requires a holistic approach, including demining, soil clean-up and planting new trees.

The war not only destroyed natural habitats but also directly affected rare and endangered species of animals and plants. These species include the black stork, lynx, marsh reed and white lily (Soils and war..., 2024). As a result of the hostilities, populations of local species that were previously characteristic of certain ecosystems have declined or even disappeared. For instance, the reduction in the number of wild animals due to the mining of territories and destruction of their natural habitats has led to the complete disappearance or substantial reduction in the number of some species, such as wild animals that lived in forests. What is particularly important is that the disappearance of certain species can have long-term consequences for ecosystems. For instance, the disappearance of predatory animals such as lynx can lead to the overpopulation of their prey, causing an imbalance in ecosystems.

The structure of flora and fauna populations has undergone significant changes in the areas of active hostilities. Soil degradation and environmental pollution have become the main factors affecting the flora. Plants are either dying or spreading to areas with more favourable growth conditions. For animals, the biggest threats are the destruction of nesting sites and deaths from explosions and landmines. This has resulted not only in a decline in the number of individual species but also in the disruption of natural food chains and ecological interactions. For instance, the disappearance of certain animal species that were an important part of the food chain can affect other species that used them as food or competitors (Can soil be cured..., 2023).

Explosions, artillery shelling and the use of ammunition have caused significant soil and water contamination. Toxic substances, such as heavy metals, nitrates and organic toxins, are accumulating in the soil and water resources, posing a threat to human and animal health. This pollution makes it difficult to restore ecosystems, as toxic substances can kill plants and animals trying to settle in these areas. Poor water and soil quality also make it difficult to restore natural resources. Statistics show that the level of water pollution in the combat zones in Ukraine far exceeds the permissible standards. For instance, as of the end of October 2022, Russian troops illegally used about 410 million m^3 of water, causing damage worth almost UAH 15.5 billion. In addition, damage to hydraulic structures, such as the Oskilske Reservoir, has led to significant environmental losses, including the death of about 2 million fish worth UAH 883.7 million. This data confirms that the level of water pollution in the war zones exceeds the permissible standards by several times (Munitions and chemicals..., 2022). This creates serious environmental problems, as contaminated water can lead to diseases in animals and people who depend on this water for their needs.

One of the most evident problems associated with the war is the physical destruction of forests as a result of hostilities. Artillery shelling, air strikes, use of armoured vehicles and explosive devices lead to massive destruction of tree cover. Forests that have long formed unique ecosystems can be destroyed in a short period as a result of intense hostilities. In addition, shell and rocket explosions create craters that disrupt the structure of the soil. This leads to soil erosion, making it impossible for vegetation to regenerate naturally. The loss of fertile soil becomes an obstacle to forest regeneration even after the hostilities stop. Restoration of such lands takes decades and, in some cases, even special environmental programmes. Another threat is the mining of territories. Forests are often used as a natural barrier during hostilities, which leads to the massive installation of minefields. This makes the area unsuitable not only for economic activity but also for natural ecosystem recovery. Wildlife migrating through such dangerous areas can become victims of mines, which negatively affects populations of many species. Mine action also hampers the efforts of ecologists and foresters who could be involved in restoring destroyed ecosystems. Another consequence of war is forest fires caused by explosions, shelling or the use of incendiary munitions. In contrast to natural fires, which can be part of the natural process of forest regeneration, military fires are uncontrollable and destroy large areas of ecosystems. They cause a loss of biodiversity, as fire destroys not only trees but also the habitats of many species of animals and plants. In addition to physical destruction, war causes large-scale environmental pollution. As a result of hostilities, heavy metals, fuel residues, and toxic substances from ammunition and explosives get into the soil and water bodies. For example, lead, mercury and cadmium contained in munitions fragments can persist in the soil profile for a long period, inhibiting plant growth and making it difficult for plants to grow (Table 2). Water contamination is another serious problem (Review of the year..., 2023). Explosions and the destruction of infrastructure cause toxic substances to enter rivers and lakes, which negatively affects the state of aquatic life. As a result, many natural water sources become unfit for human consumption, affecting both human and animal populations that depend on these ecosystems.

Table 2. The destruction of Ukrainian forest ecosystems as a result of the war and the level of their pollution

Location	Lead (Pb) concentration, mg/kg	Cadmium (Cd) concentration, mg/kg	Other pollutants
Izium Forest (Kharkiv region)	450 (at the rate of 32)	6.5 (at the rate of 0.5)	Mercury, copper, tin
Sviatohirsk National Park (Donetsk region)	390 (at the rate of 32)	5.2 (at the rate of 0.5)	Arsenic, uranium
Forests around Chernihiv	280 (at the rate of 32)	3.8 (at the rate of 0.5)	Petroleum products
Forests near Kherson (after flooding)	320 (at the rate of 32)	4.1 (at the rate of 0.5)	Heavy metal salts

Source: developed by the authors based on the Nature Reserve Fund of Ukraine (n.d.)

In times of war, control over the use of natural resources is significantly weakened. This creates ideal conditions for illegal deforestation. Due to economic instability and reduced government control, many people are forced to engage in illegal logging as a means of survival. In addition, the destruction of environmental protection institutions and their archives makes monitoring and conservation of forests much more difficult. Uncontrolled deforestation leads to further deterioration of ecosystems. Forests that were already damaged by the hostilities are under additional pressure from illegal logging. This not only reduces the total area of forests but also accelerates soil degradation and upsets the natural balance of the region. The destruction or weakening of environmental protection institutions also means that ecosystem restoration will be difficult after the end of hostilities. The lack of adequate funding and expertise makes it difficult to implement environmental programmes aimed at preserving and restoring forests.

The war negatively affects forest ecosystems, which is manifested in the physical destruction of tree cover, environmental pollution, forest fires and uncontrolled use of natural resources. Restoration of such areas is a complex and long-term process that requires significant financial, technical and human resources. To minimise the effects of the war, it is necessary to develop comprehensive forest restoration strategies, including mine clearance, clean-up of contaminated soils, restoration of biodiversity and strengthening of control over the use of forest resources. International cooperation in the field of environmental security is also important, as the war affects not only individual regions but also the global ecosystem.

Economic consequences of forest degradation. Forest ecosystems are substantial not only in the ecological balance but also in shaping the economic stability of regions. Forests provide timber and non-timber resources, perform protective functions for agricultural land, and are an important factor in the development of tourism. However, as a result of the war, forests are being significantly degraded, which negatively affects the national economy. Reduced forest resources, deteriorating soil quality and loss of recreational potential cause financial losses at both local and national levels. Economic losses include the direct loss of timber, losses of companies involved in the harvesting and processing of forest resources, and a drop in timber exports. In addition, forest degradation leads to a significant reduction in agricultural yields due to deteriorating soil quality, increased erosion and increased drought risk. This requires additional costs for land reclamation. Damage to forest plantations and a decline in forest resources have also resulted in a decline in budget revenues from the forestry sector, which has a significant impact on the financing of local administrations and infrastructure projects. Table 3 shows the main quantitative indicators of economic losses caused by the degradation of forest resources as a result of the war.

Table 3. Economic consequences of forest degradation in Ukraine (2020-2028)

Metric	2020 (before the war)	2024 (during the war)	2028 (after the war) forecast
Amount of forest fires	2,000 cases	3,500 cases	2,000 cases
Area of forest plantations lost	1,500 ha	3,200 ha	1,000 ha
Damage caused by forest fires	UAH 10 million	UAH 30 million	UAH 10 million
Share of forests affected by the war in the total area of the forest fund of Ukraine	0%	approximately 35%	15%

Table 3, Continued

Metric	2020 (before the war)	2024 (during the war)	2028 (after the war) forecast
Losses for the forest industry from the loss of forest resources	UAH 10 million	over UAH 55 million in 2023	UAH 30 million
Costs of reforestation after fires	UAH 5 million	approximately UAH 12 million per year	UAH 6 million
Economic losses from the loss of biodiversity and ecosystem services	UAH 5 million	more than UAH 18 million per year	UAH 8 million
Decrease in forest industry revenues due to damage to forest plantations	0%	by 20% compared to the pre-war level	by 10% compared to the pre-war level
Number of jobs lost due to forest degradation	0 persons	over 6,000 people are employed in the forestry industry	4,000 persons
Investments in reforestation and forest fire fighting	UAH 3 million	UAH 9 million per year	UAH 5 million

Source: compiled by the authors based on Kyiv School of Economics (2024)

The indicators reflect the significant impact of the war on Ukraine's forests, including large-scale fires, degradation of forest ecosystems and economic losses. The hostilities have affected a large part of the forest fund, resulting in a decrease in biodiversity, reduced forestry revenues and job losses. Expenditures on reforestation and firefighting remain insufficient to compensate for the damage, which requires increased attention to reforestation and natural resource protection.

Forests are an important source of resources used in various sectors of the economy. The war has led to a reduction in timber harvesting due to the physical destruction of forests, contamination of territories with explosives, and the impossibility of safe business operations. According to the State Agency of Forest Resources of Ukraine (2024), illegal deforestation increased significantly during the war, especially in areas where active hostilities were taking place. The overall reduction in timber harvesting as a result of the war is estimated at 30-40% compared to pre-war levels. Many forests are becoming dangerous due to mines, making logging and access to natural resources impossible. In addition to timber, forests provide significant amounts of non-timber resources, including mushrooms, berries, and medicinal plants. Their collection is an important source of income for the local population, especially in rural areas. The war has made some of these areas inaccessible or environmentally hazardous, reducing opportunities for collecting and selling these products. Mine action has particularly affected the availability of forest resources in eastern and southern regions of Ukraine, such as Donetsk, Luhansk and Kherson oblasts, where the fighting has been ongoing for a long time (Yutilova *et al.*, 2025). This limits not only timber harvesting but also access to forest resources for the population engaged in collecting non-timber products. The loss of forest resources directly affects the country's economic security. The forestry sector suffers significant financial losses, which affects local budget revenues. In particular, as a result of the decline in timber harvesting, which fell by 40-50% compared to pre-war levels, revenues from logging fell by 22%. In addition, a drop in exports of forest products resulted in losses of over UAH 60 million. The decline in revenues from logging and related industries has also led to the loss of more than 6,000 jobs in forestry. This leads to a decrease in tax revenues and weakens the economies of regions dependent on forest resources, creating additional social and financial difficulties. In the context of military instability, this further weakens the economy of these regions (Accounting Chamber, 2024).

Forests fulfil an important function in preserving soil fertility and regulating the water balance. Deforestation or damage to forests changes the hydrological regime, leading to a decrease in the water table. This, in turn, increases the risk of droughts, negatively impacting agriculture. The absence of forests also contributes to soil erosion. Forest roots hold the soil cover in place, preventing it from eroding and losing its fertile layer. Forest degradation increases the risk of dust storms, which reduce soil quality and worsen conditions for growing crops. The degradation of forest ecosystems has affected large areas of agricultural land (Rybalova *et al.*, 2023). In the regions that have suffered the greatest forest losses, such as Donetsk, Luhansk and Kherson oblasts, the area of degraded land reaches more than 150,000 hectares. This has led to a significant drop in groundwater levels, which is confirmed by hydrological observations. In these regions, the water table has dropped by 15-20%, which increases the risk of droughts and decreases agricultural productivity. The decline in soil quality has a negative impact on yields, particularly for grains and oilseeds. In the areas with the greatest forest losses, such as Luhansk and Donetsk regions, yields can drop by 30-40% compared to pre-war levels. This is caused by soil erosion, reduced organic matter content and degradation of water supply, which worsens the conditions for growing crops. The decline in agricultural productivity leads to higher food prices, which creates an additional economic burden on the population. In addition, the war causes soil contamination with toxic substances, such as explosive remnants, heavy metals, fuel and chemical compounds. This worsens the environmental condition of the land, making it unsuitable for agricultural use. Restoration of such areas requires significant financial investments, and their productivity may remain low for a long time.

Due to the war, the Ukrainian forestry sector has suffered major financial losses, which has a negative impact on local budget revenues. In total, more than 60,000 hectares of forests were destroyed as a result of hostilities in the temporarily occupied territories, which is estimated at least UAH 14 billion (Vedmedenko, 2024). The destruction of forests has also led to a change in the hydrological regime, a decrease in groundwater levels and an increase in drought risks, which negatively affects agriculture. Forests are an important resource for the development of ecotourism and the recreational economy. However, the war has significantly reduced opportunities for the development of this sector. Destroyed natural areas have lost their attractiveness to tourists, and mined areas have become dangerous, making it difficult to develop green tourism. An example is the Shatsky National Park in Polissia, which has suffered from hostilities and mining. Formerly popular with tourists, in 2025 part of its territory is closed due to the danger of explosive devices. Similarly, the Dermansko-Ostromostianskyi Park in western Ukraine has been destroyed, and some of its natural routes have become inaccessible due to mining. In the Carpathian region, despite the absence of active hostilities, the overall security situation and restrictions on transport accessibility have led to a 50-60% decrease in tourist flows compared to 2021 (Report on the Program..., 2023). The tourist infrastructure in Chernihiv and Sumy regions has also suffered, with numerous tourist bases destroyed, reducing the attractiveness of recreational areas. Damage to the forestry sector has created additional financial difficulties for local communities that were dependent on tourism and forest resources before the war. In the context of military instability, the economies of these regions are experiencing additional difficulties.

The presence of remnants of military equipment, infrastructure destruction and environmental pollution also have a negative impact on the development of the recreational economy. Sanatoriums, tourist resorts and natural parks that used to bring income to the region may remain abandoned or destroyed. Restoring tourism potential requires significant time and financial resources, which creates additional difficulties for the affected regions. The degradation of forest ecosystems as a result of war has serious economic consequences. The loss of forest resources reduces forest sector revenues and deprives local people of the opportunity to use natural resources. Deteriorating soil conditions negatively affect agricultural productivity, increasing the risks of erosion, drought and pollution. In addition, the destruction of natural areas reduces the country's tourism potential, depriving local communities of the opportunity to earn money from ecotourism. Losses in Ukraine's gross domestic product (GDP) due to forest degradation and the decline in their ecosystem services can reach up to 1.5% annually. Illegal deforestation is also gaining alarming proportions: during the war, its volumes have increased by at least 30%, resulting in annual losses to the state budget of more than UAH 2 billion due to lost tax revenues and shadow timber trafficking (Petrychenko *et al.*, 2022). To reduce economic losses, it is necessary to implement measures to restore forest ecosystems, control illegal logging and minimise the effects of environmental pollution. It is also important to attract investment in restoring tourism infrastructure and cleaning up natural areas. A comprehensive approach to addressing these issues will not only help restore forests but also stabilise the national economy.

Threats to national security due to forest degradation. War not only causes direct human losses and destruction of infrastructure but also poses serious threats to national security due to environmental degradation. In this context, environmental security is seen as an integral part of national security, as environmental degradation directly affects public health, food stability, economy and territorial governance. Forest ecosystems, which perform key ecological, economic and social functions, are undergoing significant destruction, which has long-term consequences for the country. The loss of natural resources, environmental pollution and climate change are making it harder for the economy to recover and exacerbating social problems. The decline in forest cover also reduces nature's ability to regenerate itself, making it more difficult to overcome the environmental crisis. Environmental experts estimate that the total area of forests damaged or destroyed by the hostilities is over 3.5 million hectares, of which a significant portion needs to be fully restored. More than 450,000 hectares of forests are contaminated with mines and ammunition, making it impossible to use them and restore natural processes. As a result of the hostilities, the level of soil contamination with heavy metals and toxic substances has increased 5-10 times compared to the pre-war period. In addition, more than 320,000 hectares of forests have burned due to massive fires caused by shelling, which has led to a significant loss of biodiversity and disruption of ecosystem links (Melnykovych *et al.*, 2025).

One of the main challenges to national security is the deterioration of the country's environmental situation. Hostilities cause massive pollution of water resources, soil and air with toxic substances. Rivers, lakes and groundwater are at risk of being contaminated by explosive residues, heavy metals (lead, cadmium, mercury, copper, nickel) and oil products. In particular, as a result of the destruction of fuel storage facilities and military equipment, benzene, toluene and polycyclic aromatic hydrocarbons with carcinogenic effects are released into water bodies. In some regions, such as Donbas, Luhansk and Kharkiv, the concentration of nitrates and sulphates in groundwater has been recorded as exceeding the norms by 5-10 times, which poses a threat to the health of the population, which may consume contaminated water or be exposed to toxic substances through food. In addition to water pollution, the destruction of forests has a significant impact, as they play an important role in maintaining air quality. Forests absorb carbon dioxide and filter out harmful substances, but their destruction significantly reduces this natural ability. Explosions and fires release large quantities of fine dust, dioxins, nitrogen oxides and heavy metals into the air, which increases air pollution (Bayegizova *et al.*, 2024). There is a 30-50% increase in the concentration of harmful substances in the air in areas of active hostilities. This has serious consequences for public health. There has been an increase in cases of respiratory diseases, asthma and bronchitis, and a rise in cancer rates, especially in regions with significant chemical pollution. In the areas of environmental disaster, the number of respiratory diseases and cardiovascular pathologies has increased by 20-25%, which underscores the need for urgent measures to restore the affected areas to a healthy state (Kolawole & Iyiola, 2023).

Forest degradation affects not only the ecological state but also the social situation in the country. A large part of the population, especially in forested regions, depends on forestry for jobs and income. Deforestation, landmines and environmental pollution lead to job losses in the forestry sector and related industries such as wood processing, tourism and agriculture. Rising unemployment is exacerbating social tensions and increasing the risk of economic instability. In addition to economic difficulties, forced displacement is a serious problem. Environmental pollution and the destruction of forest ecosystems can make some areas uninhabitable. Due to water pollution, soil degradation and landmines, the number of internally displaced people has exceeded 150,000 in the war-affected regions. The situation is most critical in the frontline areas, where large areas of forest remain unsafe for living and business. Lack of clean water, soil contamination and risks from mines are forcing people to leave their homes and seek safer places to live. This creates an additional burden on other regions and exacerbates the problem of internal displacement (Pandya & Didwania, 2021).

Forests are key in climate regulation, and their loss has serious consequences for the ecological balance. Destruction of forest cover contributes to rising temperatures, as fewer trees can absorb carbon dioxide and reduce the greenhouse effect. This can exacerbate global warming, increase the frequency of droughts and alter precipitation levels, which negatively impacts agriculture and water supplies. In some regions, such as Donbas and Luhansk, where forests have been heavily damaged by the hostilities, climate conditions are changing, including an increase in average annual temperature by several degrees and a decrease in precipitation, which is exacerbating water shortages. In addition to the impact on climate, the decline of forest ecosystems leads to the loss of ecosystem services that ensure the natural resilience of the environment. Forests help to retain moisture, prevent soil erosion and maintain biodiversity, which is essential for maintaining the natural balance. War destroys ecosystem functions such as water conservation, dust storms and soil erosion protection. This leads to increased erosion of forests and adjacent lands, more dust storms and deterioration of water quality, which creates additional challenges for local communities, agriculture and ecosystems in general. The destruction of these ecosystems reduces resilience to climate change and complicates recovery from environmental disasters (Ma *et al.*, 2022).

The degradation of forest ecosystems as a result of the war poses serious challenges to Ukrainian national security. Water, air and soil pollution threatens public health, while the loss of forest cover increases climate risks and reduces the natural capacity for self-healing. Social problems related to unemployment in the forestry sector and forced resettlement increase tensions in society and hinder economic recovery. To mitigate these threats, it is necessary to develop comprehensive measures for forest restoration, environmental monitoring and climate change adaptation. It is particularly relevant to control pollution, demining and support the socio-economic development of war-affected regions. Only a combination of environmental, economic and social initiatives will ensure the country's long-term stability and security. International initiatives aimed at restoring the natural environment after the war include the United Nations Decade on Ecosystem Restoration (2021-2030) (2019). This initiative provides technical and financial assistance to countries affected by conflicts to restore forest ecosystems and contaminated areas, including through tree planting, demining, and sustainable forestry practices. Another important initiative is the Global Environment Facility (2024) fund, which finances ecosystem restoration projects, including reforestation, water conservation and climate change mitigation measures. One example of the implementation of this programme in Ukraine is the support of projects to restore forest ecosystems in areas affected by military operations, as well as measures to improve resilience to environmental disasters. Regulation (EU) 2024/1991 of the European Parliament and of the Council (2024) supports countries in restoring biodiversity and forest ecosystems after conflicts. In Ukraine, this programme has funded projects aimed at de-mining forest areas and cleaning up pollution, particularly in regions affected by the fighting, such as Donbas. Thus, the integration of international assistance and national efforts is key to the effective restoration of the natural environment and ensuring stability in Ukraine after the war.

Key strategies for restoring forest ecosystems in Ukraine. The war has severely damaged Ukrainian forest ecosystems, making it difficult for them to recover naturally and requiring comprehensive restoration measures. In addition to physical destruction, the environmental crisis is caused by landmines, soil and water pollution, and uncontrolled logging. Forest restoration requires a systematic approach that combines environmental, technological, economic and social initiatives. Effective strategies need to be developed to clean up the areas, reforest, strengthen control and attract investment.

One of the most acute problems in forest restoration is mined areas, which makes any environmental protection measures impossible (Fig. 1). Under natural conditions, forest restoration in such areas can take decades. At the same time, the use of adaptive methods such as phytoremediation (soil cleansing by plants) and controlled afforestation with resistant tree species can significantly speed up the process (Guidi Nissim *et al.*, 2023). Effective restoration requires a combination of natural mechanisms and active measures, including ecological demining, improvement of soil characteristics, and the involvement of specialised reforestation programmes.

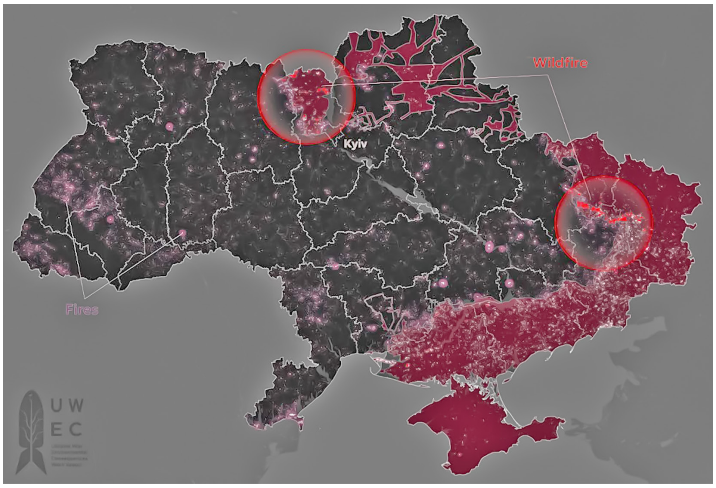

Figure 1. Map of Ukraine showing mined forest areas
Source: O. Vasylyuk *et al*. (2024)

In Ukraine, large areas of forests, particularly in the east and south of the country, are subject to demining due to the hostilities (Flamm & Kroll, 2024). This process takes a long time, which significantly complicates the natural recovery of forest ecosystems. Natural forest regeneration in such regions is ineffective due to physical damage to the soil cover, pollution, and a lack of biodiversity. Destroyed forests do not have the natural conditions for rapid regeneration, as soils lose fertility after hostilities due to explosions and erosion, as well as toxic pollution with heavy metals and chemicals. Natural forest regeneration becomes even more difficult in areas where there is a high concentration of mines and unexploded ordnance, as this is not only dangerous but also makes any environmental initiatives ineffective until the areas are cleared of mines. Therefore, to restore forest ecosystems in the affected regions, it is necessary to implement comprehensive measures, including environmental demining and sustainable forest management. Millions of hectares of forests have been mined, which seriously complicates the restoration of these areas. Effective demining requires the use of modern technology, including the creation of detailed minefield maps and the use of robotic systems to safely dispose of explosive ordnance. In addition to the mine threat, chemical contamination of soils caused by explosions, toxic emissions and other anthropogenic impacts is a serious problem. One of the most effective methods of soil remediation after such contamination is phytoremediation, i.e., the use of plants that can absorb and neutralise toxic substances. For instance, sunflower and mustard are effective at extracting heavy metals, and some tree species can neutralise oil compounds and other chemical pollutants. This method has already been used in other countries, including after military conflicts in the Balkans, where phytoremediation helped restore soils after contamination with explosives and other toxic materials (Kumar *et al.*, 2025). In addition to phytoremediation, other alternative remediation methods can be used to restore soil fertility. For example, mechanical cleaning of contaminated areas, which includes the removal of toxic materials and restoration of soil structure. The introduction of biofertilisers and organic materials also helps to improve soil conditions, by increasing humus content and improving water permeability. An integrated approach that combines phytoremediation with classical reclamation methods will ensure the effective restoration of forests and soil resources affected by the war.

In the eastern and southern regions of Ukraine, which have become the main areas of hostilities, wetlands have been severely affected. This has resulted in a disruption of the natural water balance, deterioration of water quality, and a decrease in biodiversity, as these areas are important habitats for many species of flora and fauna. Areas belonging to such natural complexes as the Kherson floodplains, the floodplains of the Don and Dnipro rivers, as well as nature reserves and sanctuaries in Donbas have been affected. The loss of wetlands disrupts the hydrological regime, which in turn makes it difficult to restore other ecosystems. Forest restoration should be based on adaptive approaches that consider climate change and the specifics of the affected regions. To this end, it is important to implement massive tree-planting programmes using drought- and disease-resistant species. For example, in the steppe regions, it is advisable to plant acacia and oak, which are better adapted to higher temperatures. In addition to the direct restoration of tree cover, it is important to maintain natural ecosystem processes, including water balance. Restoring wetlands will help to conserve biodiversity, improve water quality, and increase the resilience of forest ecosystems to climate change (Adie & Lawes, 2022).

Conservation and restoration of forests are impossible without effective monitoring of their condition. Satellite technology and drones can be used to quickly detect illegal logging, disease outbreaks and forest fires. Remote monitoring data will help to respond to environmental threats in a timely manner and optimise restoration strategies. Ukraine has already implemented projects that use satellite technology to monitor forests, including projects implemented through cooperation with international partners such as the European Union. One such project is Forest Monitoring using Sentinel satellites, which can be used for monitoring of the state of forests and prompt detection of changes in forest cover (Mozghovyi *et al.*, 2024). In addition to technological control, it is important to increase liability for environmental crimes. Stricter sanctions should be introduced for illegal deforestation and pollution of natural areas. It is advisable to increase penalties for those involved in illegal deforestation and to create a system of compensation for the affected areas, including fines for companies that violate environmental standards. At the same time, it is necessary to introduce measures to encourage businesses to use forest resources sustainably, for example, through tax incentives for companies that implement eco-strategies (Scheper *et al.*, 2021).

Restoration of forest ecosystems requires significant financial expenditures, so attracting international resources is extremely important. One such support mechanism is the introduction of environmental insurance for forestry enterprises. This will help compensate for losses from environmental disasters and promote a more responsible attitude of businesses to natural resources. For instance, Germany and Switzerland have successfully operated environmental insurance systems that insure forestry companies against damage caused by forest fires, pests, or natural disasters (Mansourian *et al.*, 2021). This experience can be adapted in Ukraine, providing compensation for the loss of forest resources and reducing environmental threats. The introduction of environmental insurance in Ukraine will help to create a financial cushion for forestry enterprises and ensure the sustainable development of the forestry industry.

Forest restoration requires the active participation of society (Tolochko *et al.*, 2024). Environmental education is substantial in this process, helping to shape the environmental culture of the population. Educational campaigns among schoolchildren, students and the military will help to understand the importance of forests and the need to protect them. In addition to education, it is necessary to engage local communities in direct participation in forest restoration. Volunteer initiatives, social projects, and the development of ecotourism can not only help restore nature but also become a source of income for local people. For example, the Million Trees for Ukraine project brought together volunteers, government organisations, and private companies to plant trees in areas affected by environmental disasters. The Forest Recovery project aims to restore forest ecosystems affected by the war by reforesting and cleaning the soil from heavy metal and explosive contamination. Through the implementation of a reforestation programme with adaptive species and the use of phytoremediation technologies, the project helps to restore biodiversity and improve the ecological condition of the affected areas.

Restoration of forest ecosystems in the wartime and post-war period is a complex but necessary task for Ukraine's environmental security. A comprehensive approach, including demining, reforestation, strengthening of control, economic support and public initiatives, will help restore destroyed ecosystems and prevent further forest degradation. International cooperation and investment are particularly important, as only joint efforts can ensure a sustainable and secure future for Ukraine's forests. Restoration of the natural environment is not only an environmental but also a socio-economic process that requires the active participation of all citizens and government institutions.

Discussion

The results of the study demonstrated that the war has a devastating impact on forest ecosystems, causing physical destruction of tree cover, large-scale fires, soil and water pollution with toxic substances, and uncontrolled use of natural resources. The study determined that a significant part of the forests in Ukraine have been damaged, making it difficult for them to regenerate naturally. Thousands of hectares of forests are minefields, rendering them unsafe for any activity, including environmental restoration initiatives. The impact of the war on forests has long-term consequences, as soil damage, pollution and loss of biodiversity can affect ecosystems for decades.

This problem was also studied by P. Pereira *et al.* (2022), confirming that the physical destruction of forests during war is one of the greatest threats to ecosystems. Explosions, artillery shelling and fires caused by hostilities can lead to massive tree destruction, soil disturbance and changes in the hydrological regime. This destroys not only the forests themselves but also the vital ecological functions they perform, including air purification, water protection and biodiversity. R.J. Wenning & T.D. Tomasi (2022) also demonstrated that the effects on forest ecosystems can be long-lasting. In addition to the direct destruction of trees, war also leads to changes in the composition of vegetation and the regeneration of forests after hostilities. Local species of flora and fauna can be drawn into the war zone, putting them at risk of extinction or displacement, and disrupting the natural balance of the ecosystem. Notably, the destruction of forests during the war has far-reaching environmental consequences that can affect the stability of climate conditions and regional hydrological cycles. Destruction of forests not only reduces carbon dioxide absorption, which increases the greenhouse effect, but can also lead to a decline in water quality due to soil erosion and water pollution (Moroz, 2024). Given that forest ecosystems are critical to maintaining the balance of nature, their destruction in war has the potential for long-term environmental disasters, even after the fighting ends.

One of the most critical problems is the physical destruction of forests as a result of hostilities. Artillery shelling, air strikes and the use of heavy machinery led to the destruction of forests. The explosions create craters that change the structure of the soil, making it unsuitable for vegetation regeneration (Fedoniuk *et al.*, 2024). Affected areas often remain barren for a long time due to the loss of the fertile layer. In addition, mined forests become dangerous for wildlife, leading to a decline in populations of rare species. Such ecological changes can be irreversible, making it difficult to restore forest resources. F. Rodriguez-Jimenez *et al.* (2024) concluded that forest fires caused by military operations are one of the biggest threats to forest ecosystems. Artillery shelling, air strikes, and explosions can not only cause outbreaks but also make them uncontrollable due to the lack of resources for rapid response. In times of war, fire can quickly spread over large areas, making it difficult to extinguish and leading to even greater destruction of forests. X. Meng *et al.* (2023) determined that the uncontrolled spread of fire in wartime often has catastrophic consequences for the environment and people. Fires can destroy large areas of forests, reducing biodiversity and degrading soil conditions. In addition, fire can pollute the air with toxic smoke, exacerbating public health problems and increasing the negative impact on the climate. These results confirm the above study, as they demonstrate a direct correlation between military operations and large-scale forest fires. The use of high-precision technologies, such as satellite imagery, shows that forests in areas of active hostilities are more likely to be affected by fire. In addition, analysis of the situation in conflict zones confirms that the lack of proper fire control combined with aggressive military operations significantly increases the likelihood of large-scale fires.

Forest fires caused by explosions, bombing and the use of incendiary munitions have become another serious problem. Contrary to natural forest fires, which can be part of the ecosystem cycle, military fires are uncontrollable and lead to the destruction of large areas (Krawczyńska *et al.*, 2024). In 2023, almost 298,000 hectares of burnt forests were recorded in Ukraine. This not only contributes to the loss of biodiversity but also worsens the air quality and causes large amounts of carbon dioxide emissions. As entire forest ecosystems are destroyed, biodiversity restoration requires significant resources and time. The study by J. Turunen *et al.* (2021), which also determined that environmental pollution of forest areas during war often has serious consequences for local ecosystems, is noteworthy. The detonation of munitions and chemicals used in hostilities can leave behind toxic residues that contaminate soil, water and air. Substances such as heavy metals, nitrates and toxic gases have long-term effects, poisoning the vegetation and animals living in these areas. In turn, C. Sonne *et al.* (2023) concluded that the toxic impact of munitions on the environment also leads to changes in the chemical composition of soils and water resources. The high concentration of toxic elements in the soil can slow down the recovery of forest ecosystems after war, hindering the process of natural regeneration. In addition, these toxic substances can accumulate in food chains, posing a risk to people and animals that interact with contaminated resources. This data is consistent with the theses presented in the previous section, as it confirms the negative impact of military operations on the ecological state of forest areas. The survey results demonstrated that the remnants of ammunition and toxic substances significantly contaminate soil and water, making it difficult to restore ecosystems. This is also consistent with previous analysis that demonstrates how long-term contamination can negatively affect biodiversity and the life cycle of forests.

The economic impact of forest degradation is also significant. The war has significantly reduced timber harvesting, which has affected the forestry industry and the incomes of local communities. Soil and water contamination makes it impossible to use forest land for agricultural purposes. Ecotourism has also been significantly affected, as the destroyed forests have lost their attractiveness to visitors and mined areas remain dangerous. Losses from the loss of forest resources and reduced revenues in related industries are estimated at millions of hryvnias annually (Strokal *et al.*, 2024). A. Daiyoub *et al.* (2024) also conducted a study that confirmed that illegal logging during wartime becomes a significant problem due to reduced control over the use of natural resources. In conflict situations, local forests often become targets of illegal exploitation, as the authorities lose the ability to effectively regulate forestry. This leads to the uncontrolled destruction of timber, which not only damages forest ecosystems but also disrupts the ecological balance in the region. L. Xia *et al.* (2023) also found that the reduced control over the use of natural resources during the war also fosters corruption and illegal timber trade. This increases the scale of deforestation, as illegal actions go unnoticed or unpunished due to the lack of appropriate control bodies. Such practices lead to the degradation of forest areas, reducing the ability of ecosystems to regenerate after the end of hostilities.

Comparing the data obtained in the course of research, it is possible to conclude that military operations significantly increase the negative impact on forest ecosystems. For instance, the increase in illegal logging in conflict zones is directly correlated with the lack of control and law enforcement that is common during war. In addition, data on toxic soil and water pollution indicate long-term environmental impacts that persist even after the end of hostilities. National security is an important issue, as forest degradation worsens the environmental situation in the country. Air, water, and soil pollution pose a threat to public health, contributing to the spread of disease and a lower quality of life (Matkivskyi & Taras, 2024). In addition, the destruction of forest cover exacerbates climate risks, such as rising temperatures and increased frequency of droughts. This could have global implications, as forests are important climate regulators and sources of oxygen. N.T. Hoang & K. Kanemoto (2021) concluded that economic losses due to forest degradation are a significant problem for countries where forest resources are an important source of income. The destruction of forests during the war leads to a significant reduction in timber production, which has a direct impact on the forest industry and the economy. The loss of ecosystem services, such as water purification and erosion protection, also has financial implications, particularly in the form of costs to restore the natural balance. M. Xie *et al.* (2022) determined that the financial impacts of forest destruction are not limited to losses from the direct destruction of timber. Forest degradation leads to reduced agricultural yields and tourism, as healthy forest ecosystems are essential for maintaining the stability of these industries. In the long term, the economic losses from the disruption of the ecological balance can be significantly greater than the initial losses from deforestation, rendering forest restoration critical to economic stability.

In general, the results of the study are consistent with the findings of other scientific works that confirm the significant and long-term negative impact of military operations on forest ecosystems. The data demonstrate a shared vision of the problem in the academic community, especially in terms of the physical destruction of forests, toxic pollution, biodiversity degradation and economic losses caused by the destruction of natural resources.

Conclusions

A study of the impact of the war on forest ecosystems in Ukraine revealed catastrophic consequences for the environment, including forests. The hostilities led to the physical destruction of forests, large-scale fires, environmental pollution and uncontrolled use of natural resources. The area of forests affected by the war has significantly decreased, with significant losses occurring in forests destroyed by fires. According to the data, the area of dead forest plantations in 2024 is 3,200 hectares, and the area of forest fires reached 3,500 cases. The area of forests destroyed by fires in 2024 was 1,150 km^2 (115,000 ha), which is significantly higher than before the war. As a result of the hostilities, approximately 3.5 million hectares of forests were affected by the war, and more than 450,000 hectares of forests were contaminated by mines and ammunition.

A substantial consequence is the pollution of the environment, which makes it difficult to restore forests. Much of the forests are contaminated with mines and ammunition, which poses a great danger to people and animals. Even more forest areas have been affected by artillery shelling and explosions, which makes it difficult to restore forest areas for a long time. The area of forests affected by artillery shelling and explosions exceeded 160,000 hectares in 2024, and by 2028, the total area of such forests is projected to reach 3 million hectares.

The war also caused a significant loss of biodiversity, as the destruction of natural habitats and disruption of ecological chains have put many species of animals and plants at risk of extinction. The decline in forest industry revenues as a result of the destruction of forest resources in 2024 is 20% compared to pre-war levels. Losses for the forestry industry due to forest degradation exceeded UAH 55 million in 2024, and biodiversity loss causes economic losses of more than UAH 18 million annually.

Restoration of forest ecosystems requires significant financial expenditures. Approximately UAH 12 million is spent annually to restore forests after fires, while investments in reforestation and forest fire fighting amount to about UAH 9 million per year. More than 2.2 million hectares of forest land require long-term restoration. This requires a comprehensive approach that includes mine clearance, environmental monitoring, phytoremediation, large-scale reforestation programmes, as well as international support and community engagement. Only through such measures can the sustainable development of forest resources in Ukraine be ensured in the future.

The importance of integrating environmental policy into national security and economic recovery strategies is particularly noteworthy, as it will help ensure the sustainability of forest ecosystems and maintain the country's socio-economic stability. The main limitation of the study is the lack of up-to-date data from the temporarily occupied and frontline territories, which makes it difficult to fully assess the extent of forest losses. The long-term environmental impact of hostilities on forest ecosystems, including the impact of soil and water pollution on natural regeneration processes, needs to be further studied.

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Conflict of Interest

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Деградація та відновлення лісових екосистем у контексті війни: екологічні та економічні виклики національній безпеці України

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Анотація. Метою дослідження було виявлення впливу військових операцій на лісові екосистеми та пошук ефективних підходів до їх відновлення в умовах екологічних та економічних викликів. Використана методологія полягала в аналізі впливу військових операцій на лісові екосистеми, оцінці економічних наслідків деградації лісів та розробці стратегії відновлення шляхом розмінування, рекультивації та впровадження систем моніторингу. У дослідженні проаналізовано масштаби руйнування лісових екосистем внаслідок війни, включаючи втрату деревного покриву, пошкодження, спричинені пожежами, гірничими роботами та механічними пошкодженнями. Дослідження встановило, що більшість лісових масивів втратили здатність до самовідновлення через зміни гідрологічного режиму та біорізноманіття. Узагальнено дані щодо забруднення ґрунту важкими металами: в Ізюмському лісі виявлено свинець 450 мг/кг та кадмій 6,5 мг/кг; у Святогірському лісі – свинець 390 мг/кг та кадмій 5,2 мг/кг; у Чернігівському лісі – свинець 280 мг/кг та кадмій 3,8 мг/кг; у Херсонському лісі – свинець 320 мг/кг та кадмій 4,1 мг/кг. Було оцінено економічні втрати від скорочення лісових ресурсів, скорочення доходів лісової промисловості та втрати робочих місць. Було проаналізовано вплив на сільське господарство, включаючи зниження продуктивності ґрунтів, ерозію та зміни мікроклімату. Було визначено соціальні наслідки, зокрема переміщення населення та зростання безробіття. Окреслено загрози національній безпеці через дестабілізацію навколишнього середовища. Обґрунтовано необхідність комплексного підходу до відновлення, що включає розмінування, обробку ґрунтів, відновлення лісів адаптивними видами та супутниковий моніторинг для запобігання незаконним вирубкам. Результати цього дослідження можуть бути використані для розробки стратегій відновлення лісових екосистем, планування екологічної політики, а також для залучення міжнародної допомоги та впровадження практик сталого лісівництва в Україні

Ключові слова: забруднення ґрунтів; видобуток корисних копалин; біорізноманіття; фіторемедіація; державна політика

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