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Age, Taxonomic, and Ecological Structures of Old Trees in Protected Natural and Man-Made Objects of Ukrainian Polissia

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Abstract. Over the past ten years, the invetnory of old trees was conducted in Ukraine. The occurence of indigenous and introduced tree species of coniferous and deciduous old trees in protected areas of Forest-Steppe, Steppe, and Ukrainian Polissia was analyzed. Currently, the issue of comparative analysis of the taxonomic and ecological structure, the frequency of occurrence of tree species from 100 years in natural and man-made protected areas of the Ukrainian Polissia is critical. The purpose of this study was to systematize the taxonomic and ecological structures, the frequency of occurrence of potentially old, old, centuries-old, and ancient trees in protected natural and man-made territories and objects of the Ukrainian Polissia. The following research methods were employed in this study: analytical, route, identification, clarification of age-related tree species according to The World Flora Online, comparative analysis. A unified scale for the distribution of old trees into four categories (potentially old (about 100 y.o.), old (100-200 y.o.), centuries-old (200-800 y.o.), ancient (800+ y.o.)) was proposed and applied, and their distribution was made. The stages of the study of potentially old, old, centuries-old, and ancient trees in the Ukrainian Polissia are given. The age structure of natural and man-made protected objects is dominated by plants from 100 to 200 years old, which is 73% and 53%, respectively. Ancient trees are represented by *Quercus robur* L., which grows in five natural sites (1% of 543 sites). Depending on the number of plants in the protected area, as well as considering the number of objects where the plants under study grow, a method has been developed for estimating their frequency of occurrence (very frequently, frequently, rarely, very rarely). It was found that potentially old, old, centuries-old, ancient trees occur very frequently – 13 taxa (21%, among which 69% are autochthonous), frequently – 13 taxa (20%, introduced (46.2%), and autochthonous (53.8 %)) and rarely – 12 taxa (19%, autochthonous species prevail 58.3%). Very rare, only on one site – 25 taxa, their number is from one to seven specimens, 76% of them are introduced. 95.2% of taxa are concentrated in man-made objects (parks-monuments of landscape art and arboretums). From 19 to 26 taxa are concentrated in four parks-monuments of landscape art created at the end of the 19th century (Vozdvyzhenskyi – 19 taxa, Vahanytskyi – 22 taxa, Polonskyi – 22 taxa, Zirnenskyi – 26 taxa). 63 taxa of potentially old, old, centuries-old, ancient trees (59 species, hybrid, three varieties) belonging to 28 genera from 16 families were found in natural and anthropogenic objects in the Ukrainian Polissia. Of them, autochthonous species make up 41.3%, introduced species – 52.4%. 90.5% of potentially old, old, centuries-old, ancient trees belong to the six categories of the Red List of the International Union for Conservation of Nature, of which 69.8% are under low threat (LC category). The biomorphological spectrum of potentially old, old, centuries-old, ancient trees is represented by megaphanerophytes (47.6%), mesophanerophytes (49.2%), microphanerophytes (3.2%). The ecological spectrum mainly comprises mesotrophs (49.2%), hemiskiophytes (49.2%), and heliophytes (39.7%), mesophytes (44.4%) and mesohygrophytes (22.2%). The obtained study results will allow monitoring potentially old, old, centuries-old, ancient trees of the protected objects of the Ukrainian Polissia over time, comparing similar trees in other territories of different regions of Ukraine, supplementing the worldwide database "Monumental trees" with information about the types of ancient trees of the Ukrainian Polissia

Keywords: centuries-old, species, parks-monuments, nature reserves, nature monuments

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Introduction

Centuries-old and ancient trees that have been formed over many centuries cannot be replaced by restoration or regeneration. Trees can grow and be resilient for centuries and die by accident, and therefore they need to be protected to preserve their priceless diversity C.H. Cannon, G. Piovesan, S. Munné-Bosch [1]. The preservation of ancient trees as a cultural value periodically decreased, which is associated with a decrease in the sense of sacredness, a decrease in control over forest plantations, changes in the use of certain species, and the loss of the value of such trees in the landscape [2]. However, ancient trees are currently valuable in providing ecosystem services to humanity. As a historical link connecting different generations of people [3], they are an important object of cultural heritage [4; 5]. Ancient trees have aesthetic and cultural values and play an essential role in regulating landscape and environmental functions [6]. Large old trees are among the largest organisms on Earth, with populations rapidly declining in many parts of the world, with serious implications for ecosystem integrity and biodiversity [7]. They are also of great ecological importance, including the hydrological regime and various ecosystem processes. Large trees affect the number of individuals of a species, their distribution over a certain period of time, as well as the populations of many other plant and animal species [8]. The diameter, height, and durability of large old trees vary depending on the species and growing conditions [7; 9; 10]. Three age classes (mature, old, and ancient) create unique evolutionary diversity in complex ecological cycles. Ancient trees form an integral part of forests that take many centuries to establish [1], play a vital role in maintaining biodiversity in forest ecosystems [11], and contribute to ecosystem integrity and biodiversity in urban and suburban areas [12]. The study of ancient trees provides an opportunity to better understand natural processes, which is especially important when developing strategies to increase tree longevity and environmental value [13]. To identify the characteristics of the growth of large trees ⩾150 years old, in Finland, their density and representation in different regions were analysed based on an inventory of forest trees for about 100 years [11]. In 198 regions of China, data were collected on trees ⩾ 100 years old, regarding the maximum age, species composition, and their density in human-dominated landscapes [14]. An inventory of old and ancient trees in Ukraine was carried out in studies [15-17]. Over the past ten years, a group of scientists has formed catalogues of old trees of the forest-steppe, steppe, and Ukrainian Polissia based on bibliographic sources and desk materials of the inventory of protected old trees [18-20]. The studies analysed the representativeness of autochthonous and introduced coniferous and deciduous species of century-old trees in administrative regions and protected areas of the forest-steppe, steppe, and Ukrainian Polissia, and provided their age structure [21-23].

However, the analysis of the taxonomic and ecological structure, the frequency of occurrence of tree species older than 100 years in the protected (natural and man-made) territories of the Ukrainian Polissia was not conducted, so this question is currently relevant.

The purpose of this study – to systematize the taxonomic and ecological structures, the frequency of occurrence of age-related, centuries-old, and ancient trees in protected natural and man-made created territories and objects of the Ukrainian Polissia.

Task: conduct an inventory of trees aged from 90 to more than 1,000 years old in the protected objects of the Ukrainian Polissia and divide them into potentially old, centenarian centuries-old, ancient trees; reveal their frequency of occurrence in natural and anthropogenic objects, establish a systematic, biomorphological, and ecological structure; distinguish dendrorarities; analyse the similarity of the dendroflora of the Ukrainian Polissia, Forest Steppe, and Steppe.

The scientific originality of the obtained study results is that for the first time a comparison of the similarity of the protected dendroflora of the old trees of the Ukrainian Polissia, Forest Steppe, and Steppe was carried out using the Serensen-Chekanovsky coefficient.

Materials and Methods

The study was conducted during 2014-2021 in four stages (Fig. 1).

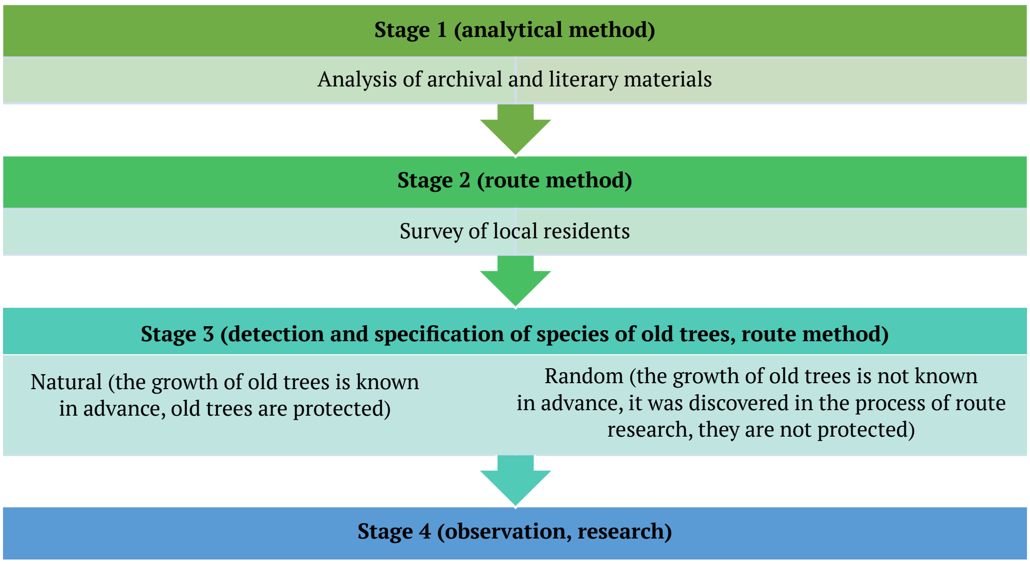

Figure 1. Scheme of the study of potentially old, centenarian, centuries-old, ancient trees

During the inventory of trees, their species [24] was identified, and the species name was specified according to the international classification [25]. Species of woody plants were verified for their pertinence to the Red List of the International Union for Conservation of Nature (IUCN Red List) [26]. The frequency of occurrence of old trees in nature reserves was determined according to the author's methodology: very rarely encoutered (1-5-7 speciments encountered in a single protected area); rarely encountered (1-5-7 specimens encountered in two to four protected areas); frequently encoutered (1-3-5-10 speciments encoutered in five to fifteen protected areas); very frequently encountered (3 or more specimens encountered in 16 or more protected areas).

Based on the methods of V.P. Shlapak, H.I. Muzyka, V.A. Vitenko, L.I. Marno [27] (old trees were divided into categories: potentially old (age – about 100 years), old (100-200 years), centuries-old (200–1,000 years), ancient (1,000 years and older)), M.O. Sovakova, O.V. Sovakov (semi-old (up to 100 years) [28], centenarian (101-300 years), multi-century (301-500 years), ancient (501-800 years), antique (800+ years), as well as considering the morpho-physiologically equivalent life stages of trees by K. Witkoś-Gnach and P. Tyszko-Chmielowiec [13], a unified scale of tree distribution into categories: potentially old (age – about 100 years), old (100-200 years), centuries-old (200-800 years), antique (800+ years). The potentially old, old, centuries-old, ancient trees were distributed into various ecological groups, considering the requirements for the main environmental factors. Life forms were classified according to C. Raunkiaer [29].

The comparison of the similarity of protected dendroflora of old trees of Ukrainian Polissia, Forest Steppe, Steppe was carried out using the Serensen-Chekanovsky coefficient [30], which is calculated according to the formula ($Csc=2c/a+b$), where a is the number of species in one object, b is the number of species in another object, c is the number of common species for the first and second objects. It shows the ratio of the number of species found in both objects at the same time to the average number of species in these objects. Binary coefficients are calculated based on the same received data, and take values from 0 ($Csc=0$, if the types of woody plants are completely different) to 1 ($Csc=1$, dendroflora is identical), if coefficient ($Csc\geq0.67$) – dendroflora is considered similar.

Results and Discussion

54 parks-monuments of landscape art (PLMAs), three dendrological parks (DP), NPP Kivertsivskyi "Tsumanska Pushcha", 18 natural monuments (NM), 9 nature reserves (NR), two protected tracts of Ukrainian Polissia were investigated, with the aim of identifying potentially old, old, centuries-old, and ancient trees. Trees were divided according to the authors' unified scale into potentially old, centenarian centuries-old, ancient, and their frequency of occurrence was established.

Based on the inventory and analysis of the list of plants [20], it was found that the age structure of natural and anthropogenic protected objects is dominated by plants aged from 100 to 200 years, which is 73% and 53%, respectively (Fig. 2), according to the number of distributions presented objects, natural – 10 times higher than anthropogenic objects. Ancient trees are represented by *Quercus robur* L., which grows only in natural objects (five in total) and accounts for 1% of their total number. The age of *Quercus robur* L. varies from 800 to 1,300 years, a 1,300-year-old specimen grows in the Yuzefinskay Dacha botanical monument of nature. Centuries-old trees within natural and anthropogenic objects make up 22% and 26%, respectively, in terms of the number of presented objects, natural ones outnumber man-made ones by more than 10 times.

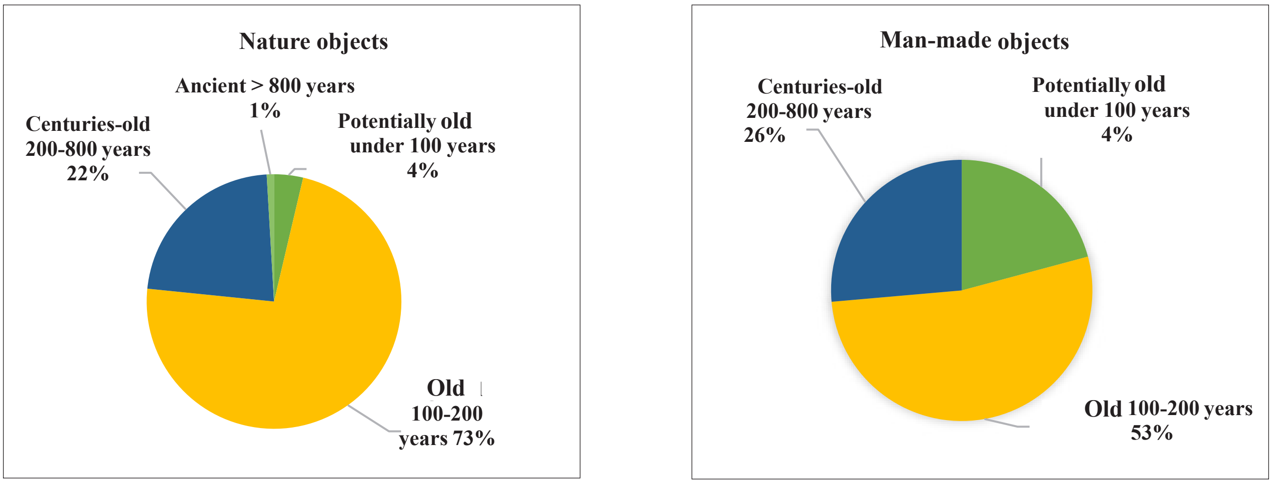

Figure 2. Age structure of potentially old, centenarian, centuries-old, and ancient trees of protected objects of Ukrainian Polissia

On the protected territories of the Ukrainian Polissia, there are very frequently (21%) – potentially old, frequently (21%) – old, rarely (19%) – centuries-old and ancient trees, a total of 38 species (Fig. 3). There are 13 species of plants that occur very frequently, among them 69% are autochthonous. *Larix decidua* Mill. (21 objects), *Picea abies* Karst. (38 objects), *Pinus sylvestris* L. (156 objects), *Quercus robur* L. (296 objects), *Tilia cordata* Mill. (48 objects), *Acer platanoides* L. (34 objects), *Carpinus betulus* L. (29 objects), *Tilia platyphyllos* Scop. (21 objects), etc.

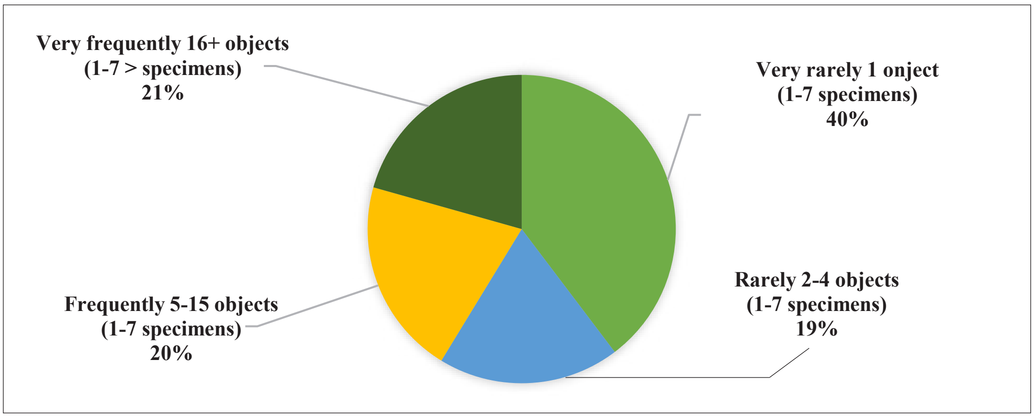

Figure 3. Frequency of occurrence of potentially old, centenarian, centuries-old, and ancient trees of protected objects of Ukrainian Polissia

Most of the old species grow in nature reserves, natural monuments and PLMAs, their number varies from 3-5-8 specimens (*Larix decidua* Mill. – Hubyn botanical reserve, Papyki forest reserve, Volyn region (Figs. 4a, 4b), PLMA Vilkhivskyi, Zhytomyr region (Fig. 5n); *Acer platanoides* L. – Sirche landscape reserve, Volyn region (Fig. 4c), PLMA Oleksandriyskyi, Rivne region (Fig. 5d) and Dvoryshchanskyi, Zhytomyr region (Fig. 5l); *Quercus robur* L. – Hamarnia landscape reserve, Zhytomyr region (Fig. 4d), PLMA Horodotskyi, Rivne region (Fig. 5a) and Kutuzov Park, Zhytomyr region (Fig. 5f), *Tilia cordata* Mill. – PLMA Ushomyrskyi, Zhytomyr region (Fig. 5k); *Tilia platyphyllos* Scop. – Volodymyretskyi Park complex monument of nature, Rivne region (Fig. 4h), *Carpinus betulus* L. – PLMA Mikluho-Maclay Park, Zhytomyr region (Fig. 5h)) to more than 30 specimens (*Larix decidua* Mill., Hubyn botanical reserve, Volyn region (Fig. 4a). Such species as *Larix decidua* Mill. (Modryna botanic monument of nature, (Fig. 4e), Piliava DP, Zhytomyr region), *Pinus sylvestris* L. (PLMA Vozdvizhenskyi, Sumy region (Fig. 5c)), *Quercus robur* L. form pure and mixed stands, where over 50 or more specimens grow – these are mostly the remnants of natural stands based on which the sanctuaries (Hamarnia labdscape reserve and others), complex monuments of nature (Antonivka Park, Volodymyretskyi park), and PLMAs (Klevanskyi Park, Vozdvizhenskyi, Miklukho-Maclay Park) are created.

a) *Larix decidua* Mill. Hubyn botanical reserve (Volyn region)

b) *Larix decidua* Mill. Papyky forest reserve (Volyn region)

c) *Acer platanoides* L. Sirche landscape reserve (Volyn region)

d) *Quercus robur* L. Hamarnia landscape reserve (Zhytomyr region)

e) *Larix decidua* Mill. Modryna botanic monument of nature (Zhytomyr region)

f) *Pinus nigra* J.F.Arnold Sosna Chorna botanic monument of nature (Rivne region)

g) *Pinus nigra* J.F.Arnold Yuzefinska Dacha botanic monument of nature (Rivne region)

h) *Tilia platyphyllos* Scop. Volodymyretskyi Park complex monument of nature (Rivne region)

Figure 4. Nature reserves of the Ukrainian Polissia (author's photo)

a) *Quercus robur* L.
Horodotskyi
(Rivne Oblast)

b) *Acer negundo* L.
Tuchynskyi
(Rivne Oblast)

c) *Pinus sylvestris* L.,
Betula obscura Kotula
Vozdvyzhenskyi
(Sumy Oblast)

d) *Acer platanoides* L.
Oleksandriiskyi
(Rivne Oblast)

e) *Ginkgo biloba* L.
Yu. Gagarin Park
(Zhytomyr region)

f) *Quercus robur* L.
Kutuzov Park
(Zhytomyr region)

g) *Pinus strobus* L.
Zirnenskyi
(Rivne region)

h) *Carpinus betulus* L.
Miklukho-Maclay Park
(Zhytomyr region)

k) *Tilia cordata* Mill.
Ushomyrskyi
(Zhytomyr region)

l) *Acer platanoides* L.
Dvoryshanskyi
(Zhytomyr region)

m) *Fagus sylvatica* L
Piliava DP
(Zhytomyr region)

n) *Larix decidua* Mill.
Vilkhivskyi
(Zhytomyr region)

Figure 5. Man-made created protected objects of the Ukrainian Polissia (PLMAs and dendrological parks) (author's photo)

Among the species that occur frequently (on 5-15 sites), introduced species and autochthons are represented by almost the same number of 6 and 7 species, respectively, and 61.5% of them were found both on natural and man-made sites. These include *Pinus strobus L.* (9 objects), including PLMA Zirnenskyi, Rivne region (Fig. 5g), *Acer negundo* L. (6 objects) – PLMA Tuchinsky, Rivne region (Fig. 5b), *Quercus petraea* (Matt.) Liebl. (9 objects), *Alnus glutinosa* (L.) Gaerth. (13 objects), *Ulmus glabra* Huds. (12 objects), *Ulmus laevis* Pall. (10 objects), *Salix alba* L. (13 objects), *Aesculus hippocastanum* L. (15 objects), *Acer pseudoplatanus* L. (7 objects), etc.

Rarely, on 2-4 objects, in the number of one to seven specimens, 12 species of potentially old, centenarian, centuries-old, and ancient trees occur, autochthonous trees predominate (58.3%), 4 species (33.3%) grow as both on natural and anthropogenic objects. These include *Acer campestre L.* (2 objects), *Betula obscura* Kotula. (3 objects), *Crataegus monogyna* Jacq. (3 objects), *Ulmus minor* Mill. (3 objects), *Salix fragilis* L. (2 objects), *Larix decidua* var. *polonica* (4 objects), *Malus sylvestris* Mill. (5 objects), *Fagus sylvatica* L. (4 objects), among them Piliava DP, Zhytomyr region (Fig. 5m), *Pinus nigra* J.F. Arnold (2 objects), including Sosna Chorna and Yuzefinska Dacha botanic monuments of nature, Rivne region (Figs. 4f, 4g), etc. In the Sosna Chorna botanic monument of nature, there is a potentially ancient plant that is represented by a mixed stand of *Pinus nigra* J.F.Arnold with an admixture of *Pinus sylvestris* L.*,* the number of *Pinus nigra* J.F.Arnold is over 30 specimens.

Very rarely, only one object, 25 taxa occur, their number is from one to seven specimens, 76% of them are introduced species. 95.2% of taxa are concentrated in man-made objects – PLMA and dendrological parks, they include *Ginkgo biloba* L. (Yu. Gagarin Park, Zhytomyr region (Fig. 5e)), *Thuja occidentalis* L., *Pseudotsuga menziesii* (Mirb.) Franco., *Quercus rubra* L., *Liriodendron tulipifera* L., *Phellodendron amurense* Rupr., *Celtis occidentalis* L., *Fagus sylvatica* subsp. *purpurea*, *Aesculus × carnea* Zeyh., etc.

In the PLMA grow between one and 26 representatives of potentially old, centenarian, centuries-old, and ancient trees. The largest number is represented in the PLMA created at the end of the 19th century, namely the Zirnenskyi PLMA (26 taxa) (*Alnus glutinosa* (L.) Gaerth., *Populus alba* L., *Quercus robur* L., *Salix alba* L., *Pinus strobus* L., *Larix decidua* Mill., *Larix decidua* var. polonica, *Pinus nigra* Arn., *Pinus ponderosa* Dougl, *Aesculus hippocastanum* L., *Acer saccharinum* L., *Acer negundo* L., *Robinia pseudoacacia* L., etc.), Vahanytskyi (22 taxa) (*Acer saccharinum* L., *Acer platanoides* L., *Pinus sylvestris* L., *Quercus robur* L., *Picea pungens* Engelm., *Aesculus ×carnea* Zeyh., etc.), Vozdvyzhenskyi (19 taxa) (*Tilia cordata* Mill., *Tilia platyphyllos* Scop., *Pinus sylvestris* L., *Quercus robur* L., *Pseudotsuga menziesii* (Mirb.) Franco., *Phellodendron amurense* Rupr., *Populus nigra* L., etc.), Polonskyi (22 taxa) (*Larix decidua* Mill., *Picea abies* Karst., *Aesculus hippocastanum* L., *Acer platanoides* L., *Fraxinus excelsior* L., etc.).

Thus, 63 taxa of potentially old, centenarian, centuries-old, and ancient trees (59 species, hybrid, three varieties) belonging to 28 genera and 16 families were found in the Ukrainian Polissia in natural and anthropogenic objects (Table 1). Of them, autochthonous species make up 41.3%, introduced species – 52.4%. Taxa of the *Magnoliophyta* division predominate. The family *Pinaceae Lindl* has the most species diversity (13 species). 90.5% of potentially old, centenarian, centuries-old, and ancient trees belong to the six IUCN Red List categories, of which 69.8% are represented by the LC category under low threat, 12.7% belong to the DD category, *Fraxinus pennsylvanica* Marsh. – critically endangered (CR category), *Aesculus hippocastanum* L. – vulnerable (VU), *Ginkgo biloba* L., *Larix decidua* var. *rolonica* – endangered (EN), *Fraxinus excelsior* L. – near threatened (NT).

Table 1. Systematic structure of potentially old, centenarian, centuries-old, and ancient trees of protected objects of Ukrainian Polissia

Family	Genus		Species		Hybrid/variety	
	Number	%	Number	%	Number	%
Ginkgoaceae Adas.	1	3.6	1	1.7		
Cupresaceae Rich. Ex Bartl.	1	3.6	1	1.7	–	–
Pinaceae Lindl.	4	14.3	13	22.0	–	–
Fabaceae Lindl.	2	7.1	2	3.4	–	–
Fagaceae A.B.R.	2	7.1	5	8.5	–/1	–/33.0
Juglandaceae A.Rich. ex Kunt.	1	3.6	1	1.7	–	–
Betulaceae S.F. Gray	3	10.7	4	6.8	–	–
Oleaceae Lindl.	1	3.6	3	5.1	–	–
Rosaceae Juss.	4	14.2	7	11.9	–	–
Ulmaceae Mirb.	1	3.6	3	5.1	–	–
Cannabaceae Martinov.	1	3.6	1	1.7	–	–
Salicaceae Mirb.	2	7.1	6	10.1	–	–
Sapindaceae Juss.	2	7.1	6	10.1	1/1	100/33.0
Rutaceae Juss.	1	3.6	1	1.7	–	–
Malvaceae Juss.	1	3.6	4	6.8	–/1	–/33.0
Magnoliaceae Juss.	1	3.6	1	1.7	–	–
Total 16	28	100	59	100	1/3	100/100

The biomorphological spectrum of potentially old, centenarian, centuries-old, and ancient trees is represented by an almost equal number of megaphanerophytes (47.6%), mesophanerophytes (49.2%), and rare microphanerophytes (3.2%). Based on the analysis of the ecological structure of the dendroflora of potentially old, centenarian, centuries-old, and ancient trees of the protected objects of Ukrainian Polissia, it was established that there are four groups in terms of demand for soil moisture – common mesotrophs (49.2%), in terms of demand for lighting, hemiskiophytes (49.2%) and heliophytes (39.7%) prevail, to soil fertility – mesophytes (44.4%) and mesohygrophytes (22.2%) (Fig. 6). These include are such plants as *Ginkgo biloba* L., *Larix decidua* Mill., *Carpinus betulus* L., *Populus tremula* L., *Tilia cordata* Mill., *Ulmus minor* Mill., *Malus sylvestris* Mill., *Pyrus pyraster* (L.) Burgsd., etc. The further development and stability of plants depends on the extent to which the environmental conditions of growth meet the requirements of plants. Under favourable conditions and protection, potentially potentially old, centenarian trees can pass into the group of centuries-old and ancient trees.

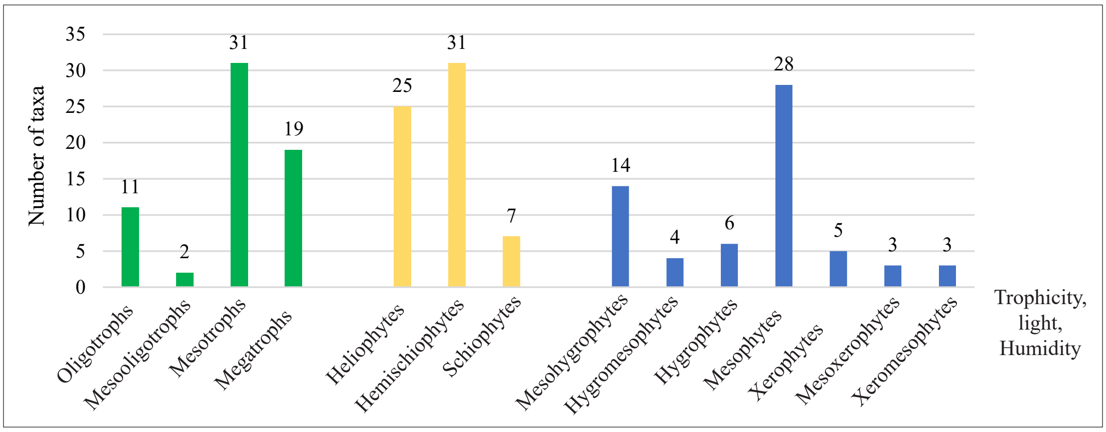

Figure 6. Ecological structure (trophicity, light, humidity) of potentially old, centenarian, centuries-old, ancient trees of protected objects of the Ukrainian Polissia

Based on own research and studies [18-20], a comparative analysis of the taxonomic composition and age structure of trees from 90 years to more than 1,000 years in three zones was carried out. The amplitude of the age of protected trees is greater in the Ukrainian Polissia (100-1,300 years) than in the Forest Steppe (100-500 years) and in the Steppe (100-250-year-old trees). In the three natural zones, age trees from 100 to 200 years prevail. 28 taxa are common to Ukrainian Polissia, Forest Steppe, and Steppe. These include *Pinus sylvestris* L., *Robinia pseudoacacia* L., *Quercus robur* L., *Quercus petraea* (Matt.) Liebl., *Juglans regia* L., *Alnus glutinosa* (L.) Gaerth., *Carpinus betulus* L., *Fraxinus excelsior* L., *Fraxinus pennsylvanica* Marsh., *Malus sylvestris* Mill., *Ulmus glabra* Huds., *Populus alba* L., *Populus nigra* L., *Acer platanoides* L., *Acer campestre* L., *Tilia cordata* Mill., etc. The number of sites in the three natural zones is dominated by *Quercus robur* L., the largest number in the Forest Steppe (486 sites), slightly smaller – in the Ukrainian Polissia (296 sites), the smallest – in the Steppe (125 sites), which is explained by the requirements for optimal growth conditions.

The largest number of old trees, including introduced species, is concentrated in man-made created protected objects in the Ukrainian Polissia (PLMAs, dendrological parks) (95.2%) in the Forest Steppe (botanical gardens, dendrological parks, PLMAs) 97.2%, in contrast to the Steppe, where 92.9% of old trees grow in natural objects (Table 2). Less than 50% of old trees in the Ukrainian Polissia (44.4%) and in the Forest Steppe (34.9%) grow in natural objects. Representatives of the families *Pinaceae* Link., *Rosaceae* Juss., *Betulaceae* S.F.GRAY are spread in three zones.

Table 2. Representativeness of old, centuries-old, ancient dendroflora of natural and anthropogenic protected objects of the Ukrainian Polissia, Forest Steppe, Steppe

Objects	Family		Genus		Taxa	
	Number	%	Number	%	Number	%
Ukrainian Polissia						
Natural	13	81.3	20	71.4	28	44.4
Man-made (PLMAs, dendrological parks)	14	87.5	26	92.8	60	95.2
Total	16	100	28	100	63	100
Forest-Steppe						
Natural	13	44.8	24	48.0	38	34.9
Man-made (PMLA, dendrological parks, botanical gardens)	28	96,	49	98.0	106	97.2
Total	29	100	50	100	109	100
Steppe						
Natural	25	89.3	48	82.7	79	92.9
Man-made (PLMAs, dendrological parks, botanical gardens)	26	92.9	54	93.1	77	90.6
Total	28	100	58	100	85	100

An intersection-similarity matrix was used to visualise correlations between the dendrofloras of old trees of three natural zones (Ukrainian Polissia, Forest Steppe, Steppe). As the analysis showed, the value of the Serensen-Chekanovsky similarity coefficient is within the limits (0.39≤Csc≥0.5) average value ΔCsc=0.45, which indicates a slight similarity of dendroflora. The maximum values of the Serensen-Chekanovsky coefficient were obtained for a pair of dendroflora: A – Ukrainian Polissia and B – Forest Steppe (Csc=0.5) (Table 3). The insignificant number of common species (Csc≤0.39) and (Csc≤0.45) were influenced by both historical, ecological and geographical factors of Ukrainian Polissia, Forest Steppe, Steppe.

Table 3. Combined matrix of cross-similarity of age dendroflora of protected objects of Ukrainian Polissia, Forest Steppe, Steppe

PLMAs		**A**	**B**	**C**
Number of species		**63**	**109**	**85**
A	**63**	–	0.5	0.39
B	**109**	43	–	0.45
C	**85**	29	44	–

Note: A – Ukrainian Polissia; B – Forest Steppe; C – Steppe, A, B, C – compared objects, numbers – the number of taxa in the objects; on a gray background – the absolute number of shared taxa for all pairs of objects, on a white background – the value of the Serensen-Chekanovsky coefficient

In studies [21-23], the authors analysed the representation of autochthonous and introduced old woody plants within the separate natural zone of the Forest-Steppe, Steppe, and Ukrainian Polissia, according to the categories of the nature reserve areas, administrative regions and localities, the old trees were divided according to the longevity of the trees. Within the boundaries of a separate natural zone, it was found that the most common species of old introduced trees are in the dendrological parks, autochthonous – in the natural monuments. The frequency of occurrence of autochthonous and introduced species depends on the natural zone and administrative region, which confirms the above results.

Conclusions

63 taxa of semi-old, old, centuries-old, ancient, centuries-old, and ancient trees belonging to 28 genera and 14 genera grow on protected natural and anthropogenic objects of the Ukrainian Polissia. 60 taxa are concentrated in anthropogenic objects and only 28 in natural ones, introducers predominate among them (52.4%). In 40% of objects, plants are very rare – from one specimen to seven. 21% of plants are very frequent representatives of natural flora (*Betula pendula* Roth., *Quercus robur* L., *Carpinus betulus* L., *Fraxinus excelsior* L., *Populus alba* L., etc.). 25 species of woody plants grow both on natural and man-made objects, including *Pinus sylvestris* L., *Pinus strobus* L., *Quercus robur* L., *Alnus glutinosa* (L.) Gaerth., *Tilia cordata* Mill., *Acer platanoides* L., etc. The ecological structure is represented mainly by mesotrophs (49.2%), hemiskiophytes (49.2%) and heliophytes (39.7%), mesophytes (44.4%) and mesohygrophytes (22.2%).

In the Ukrainian Polissia, the representatives of protected ancient trees (*Quercus robur* L.) reach the age of 1,300 years, in the Forest-Steppe – 500 years, in the Steppe – the maximum age is 250 years. The largest number of old trees is concentrated in man-made created protected objects in Ukrainian Polissia (95.2%) and in the Forest Steppe (97.2%). Historical, ecological, and geographical factors influenced the insignificant number of common species of the Ukrainian Polissia, Forest Steppe, and Steppe. Considering the value of centuries-old and ancient trees, as well as the prospects of potentially old trees (their number is the largest), it is necessary to further promote the preservation and protection of the above-mentioned trees for future generations.

Research prospects include further monitoring of potentially old, centenarian centuries-old, and ancient trees of protected objects of the Ukrainian Polissia, conducting a comparative analysis of similar trees in other territories of Ukraine, entering the received information about species into the “Monumental trees” database.

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Анотація. В Україні протягом останніх десяти років було проведено інвентаризацію вікових та старовікових дерев, проаналізовано репрезентативність автохтонних та інтродукованих хвойних і листяних видів вікових дерев заповідних територій Лісостепу, Степу, Українського Полісся. Наразі актуальним є питання порівняльного аналізу таксономічної та екологічної структури, частоти трапляння видів дерев від 100 років у природних та штучно створених заповідних об'єктах Українського Полісся. Метою дослідження було систематизувати таксономічну та екологічну структури, частоту трапляння вікових, багатовікових і стародавніх дерев на заповідних природних і штучно створених територіях та об'єктах Українського Полісся. Застосовано методи дослідження: аналітичний, маршрутний, виявлення, уточнення видів вікових дерев відповідно до The World Flora Online, порівняльний аналіз. Запропоновано та застосовано уніфіковану шкалу розподілу вікових дерев на чотири категорії (потенційно вікові (близько 100 років), вікові (100–200 років), багатовікові (200–800 років), та стародавні (800+ років)), зроблено їхній розподіл. Наведено етапи дослідження потенційно вікових, вікових, багатовікових та стародавніх дерев на Українському Поліссі. У віковій структурі природних і штучно-створених охоронних об'єктів переважають рослини від 100 до 200 років, що становить 73 та 53 % відповідно. Стародавні дерева представлені *Quercus robur* L., що зростає у п'яти природних об'єктах (1 % від 543 об'єктів). Залежно від кількості рослин на заповідному об'єкті, а також враховуючи кількість об'єктів, у яких зростають досліджувані рослини, розроблено методику оцінювання їхньої частоти трапляння (дуже часто, часто, рідко, дуже рідко). Встановлено, що потенційно вікові, вікові, багатовікові та стародавні дерева трапляються дуже часто – 13 таксонів (21 %, серед яких 69 % автохтони), часто – 13 таксонів (20 %, інтродуценти (46,2 %) і автохтони (53,8 %)) та рідко – 12 таксонів (19 %, переважають автохтони 58,3 %). Дуже рідко, лише на одному об'єкті, трапляється 25 таксонів, їхня кількість становить від одного до семи екземплярів, із них 76 % – інтродуценти. 95,2 % таксонів зосереджено у штучно-створених об'єктах (парки-пам'ятки садово-паркового мистецтва та дендропарки). У чотирьох парках-пам'ятках садово-паркового мистецтва, що створені у кінці XIX ст. зосереджено від 19 до 26 таксонів (Воздвиженський – 19 таксонів, Ваганицький – 22 таксона, Полонський – 22 таксона, Зірненський – 26 таксонів). На Українському Поліссі у природних та штучно-створених об'єктах виявлено 63 таксони потенційно вікових, вікових, багатовікових та стародавніх дерев (59 видів, гібрид, три різновиди), що належать до 28 родів із 16 родин. Із них автохтонні види складають 41,3 %, інтродуценти – 52,4 %. 90,5 % потенційно вікових, вікових, багатовікових та стародавніх дерев належать до шести категорій Червоного списку Міжнародного союзу охорони природи, із них 69,8 % знаходяться під невеликою загрозою (категорія LC). Біоморфологічний спектр потенційно вікових, вікових, багатовікових та стародавніх дерев представлений мегафанерофітами (47,6 %), мезофанерофітами (49,2 %), мікрофанерафіти (3,2%). Екологічний спектр – переважно мезотрофами (49,2 %), геміскіофітами (49,2 %) та геліофітами (39,7 %), мезофітами (44,4 %) та мезогігрофітами (22,2 %). Отримані результати досліджень нададуть можливість проводити моніторинг потенційно вікових, вікових, багатовікових та стародавніх дерев заповідних об'єктів Українського Полісся у часі, порівнювати подібні дерева на інших територіях різних регіонів України, поповнити всесвітню базу «Monumental trees» інформацією про види стародавніх дерев Українського Полісся

Ключові слова: багатовікові, види, парки-пам'ятки, заказники, пам'ятки природи

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Growth and Physiological Resilience of Pine Forests in Ukrainian Polissia

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Abstract. The main prerequisite for this study is the use of forest resources corresponding to the principles of sustainable forest management. The purpose of this study is to figure out the growth characteristics of pine stands and their physiological response to adverse factors. The experimental material (cores) was selected from pine forests of Ukrainian Polissia using Haglöf increment borer at breast height of 1.3 m. The number of annual rings and the parameters of radial increment were found using the ImageJ software. The result was a tree-ring chronology of sample trees. Statistical analysis of the experimental data proved that the radial increment variability decreases with age, and it ranges within 0.99-2.78 mm. The average radial increment value in the data set under study is 1.79 mm. The average number of annual rings of Scots pine (*Pinus sylvestris* L.) trees is 80: the minimum is 61, the maximum is 92. The correlation analysis of experimental data proved that the pairwise correlation coefficients of radial increment (-0.54) and current increment by diameter (-0.53) have an inverse relationship with the age of trees, and diameter at breast height with age – a direct relationship (0.87). The developed mathematical models of the dynamics of the width of the annual ring, the diameter at breast height and the current increment by diameter allow estimating the growth characteristics of Scots pine trees throughout their life. The obtained results were compared with the growth tables of fully stocked (at a relative stocking of 1.0) stands. The adequacy test of the developed mathematical models proved the accuracy of the given patterns and is as follows: for the width dynamics of the annual ring – 0.46; the diameter at breast height – 0.78, and the percentage of current increment by diameter – 0.51. Based on standardisation of individual chronologies by calculating sensitivity coefficients, no significant physiological response was established. Accordingly, the impact of short-term stress reactions is insignificant. The maximum resistance of pine stands to adverse environmental factors is achieved at the age of 50-60 years. This study is important to evaluate the impact of climate change and other adverse factors on the growth of pine stands and forecasting the dynamics of biometric indices. The obtained results can be used by the specialists at IA "Ukrderzhlisproekt" to update biometric indices and substantiate the use of forest resources

Keywords: Scots pine, tree-ring chronology, sensitivity coefficients, current increment by diameter, radial increment

Introduction

The sanitary condition of pine stands in Ukrainian Polissia requires thorough research to establish the cause-and-effect relationships that led to its deterioration. The study of the growth of pine stands in Polissia revealed differences in the parameters of radial increment in areas of intensive economic activity and where such activity was prohibited due to radioactive contamination. Standardisation of individual chronologies and calculation of sensitivity coefficients allow establishing the physiological stability of Scots pine trees in forests [1], i.e., estimating the level to which physiological stress affects the growth and development of the stand. It was found that during the entire period of growth, pine stands undergo physiological stresses, as evidenced by the data from other studies [2; 3].

The growth of trees in a stand is dictated both by the influence of external (microclimatic, soil-hydrological, etc.) factors, and by the physiological features of the tree species. The radial increment of trees depends on the response of the genotype to the amount of precipitation and heat [4] and their distribution during the year. The dynamics of the radial increment of Scots pine trees in various coenopopulations and selection categories of the western

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region showed no significant differences [5]. At the same time, the sensitivity coefficient showed substantial individual variability within the selection categories. Apart from the influence of adverse natural and climatic factors on the growth of trees, it was found that the stability of trees is reduced due to intensive recreational activity [6]. Conducting dendrochronological research requires varied information about natural and anthropogenic factors that can affect tree growth and the variability of indices. A rapid decrease in growth may be associated with interspecific competition [7]. The radial increment value is affected by the thinning of forests both due to planned maintenance felling and sanitary felling [8], as well as the established effect of fires [9].

Climate changes adversely impact the growth and development of pine stands everywhere, not only in Ukraine [10-12]. In contrast to the Forest Steppe, adaptation is much slower in Polissia, leading to massive drying up of stands in large areas [2].

The purpose of this study was to identify the parameters of radial increment, the dynamics by diameter and its current increment. Additionally, it was to establish the physiological resistance of Scots pine trees to adverse factors.

The results of this paper found the physiological stability of Scots pine trees in the region under study. Additionally, mathematical models of the width dynamics of annual ring, diameter at breast height (DBH), and current increment by diameter were developed, which forms the scientific originality of this study.

Materials and Methods

The study was conducted on temporary sample plots in 2020-2021. The wood samples (cores) were selected in pine stands of Ukrainian Polissia, namely: in the State Enterprise “Kamin-Kashyrskyi Forestry” in the Volyn Oblast (22 cores) and in the State Enterprise “Zarichany Forestry” in the Zhytomyr Oblast (22 cores).

The wood samples were selected using a Presler borer (*Haglöf*) at a breast height (1.3 m) [2; 13; 14]. In laboratory conditions, the cores were pasted on a special wooden substrate. Subsequently, the cores were carefully sanded and scanned. For further research, the annual rings of the sample trees were dated and measured with the *ImageJ* software and a special *ObjectJ* plugin (Fig. 1). This provided the results of the tree-ring chronology.

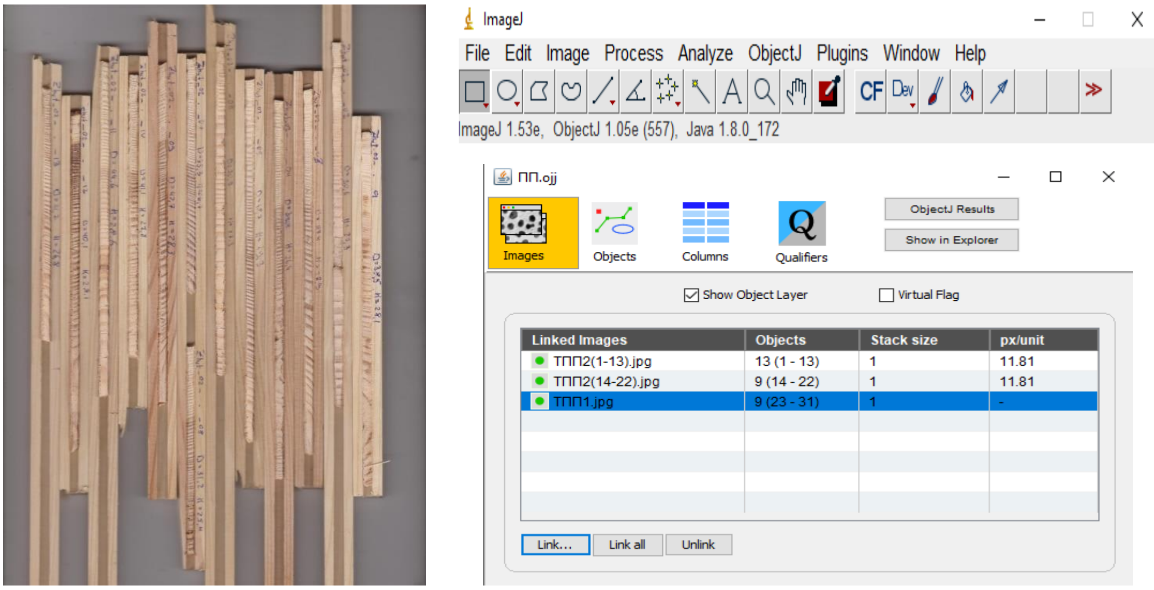

Figure 1. Processing of experimental data using the *ImageJ* programme

The data array obtained through processing of wood samples contained information on the number of annual rings and annual radial increment. The tightness of the relationship between the values under study was established using the correlation analysis [15]. Further research was carried out using the *MS Excel spreadsheet.* The characteristics of the experimental data are presented in the Table 1.

Table 1. Statistical characteristics of experimental data

No.	Number of rings	Mean increment, mm	Standard deviation	No.	Number of rings	Mean increment, mm	Standard deviation
1	76	1.95	2.01	23	89	1.51	0.82
2	85	1.34	1.23	24	78	2.19	0.89
3	78	2.38	2.77	25	90	1.62	0.97
4	80	1.73	1.17	26	77	2.11	1.12
5	83	2.20	1.22	27	85	1.87	0.80
6	69	2.40	2.27	28	78	1.75	0.85
7	72	1.64	1.06	29	86	1.58	1.07
8	77	1.37	0.59	30	89	1.71	0.87

Table 1, Continued

No.	Number of rings	Mean increment, mm	Standard deviation	No.	Number of rings	Mean increment, mm	Standard deviation
9	84	1.91	1.45	31	79	1.42	1.21
10	87	1.65	1.23	32	81	1.66	1.66
11	61	2.78	2.55	33	82	1.75	1.15
12	67	1.86	2.66	34	88	1.97	1.10
13	69	1.86	1.84	35	75	1.50	1.38
14	92	2.02	1.52	36	69	1.43	0.53
15	66	2.78	1.19	37	90	1.71	1.45
16	91	1.86	1.71	38	88	1.50	1.81
17	63	1.75	0.59	39	83	1.71	1.09
18	70	2.05	1.67	40	89	1.75	1.07
19	77	2.37	0.93	41	90	1.65	1.03
20	89	2.00	1.24	42	88	1.65	0.74
21	78	0.99	0.71	43	76	1.14	0.85
22	77	1.77	1.00	44	89	1.51	0.82
Mean:						1.79	1.41

The average radial increment is a variable, as evidenced by the standard deviation. Notably, with increasing age, the variability of radial increment decreases, especially for trees above 80 years old. This trend may indicate the intraspecific competition of trees in the growth process. The radial increment of Scots pine trees ranged within 0.99-2.78 mm, and the mean value was 1.79 mm.

Results and Discussion

To investigate the growth of Scots pine trees, the results of tree-ring chronology were used. Mathematical modelling involved the method of least squares [16], which minimises the sum of squares of the deviation between factual and simulated values. The power equation (1) of the following type was used as a basis:

$$y = a_0 \cdot A^{a_1} \qquad (1)$$

where a_0, a_1 are the equation parameters; A is the age of trees, years.

Based on the results of tree ring dating and correlation analysis, it was established that the pairwise correlation coefficient (r) between annual ring width and age is -0.54. Graphical analysis of experimental data and results of mathematical modelling of the width dynamics of annual ring (Δ_r) (Fig. 2).

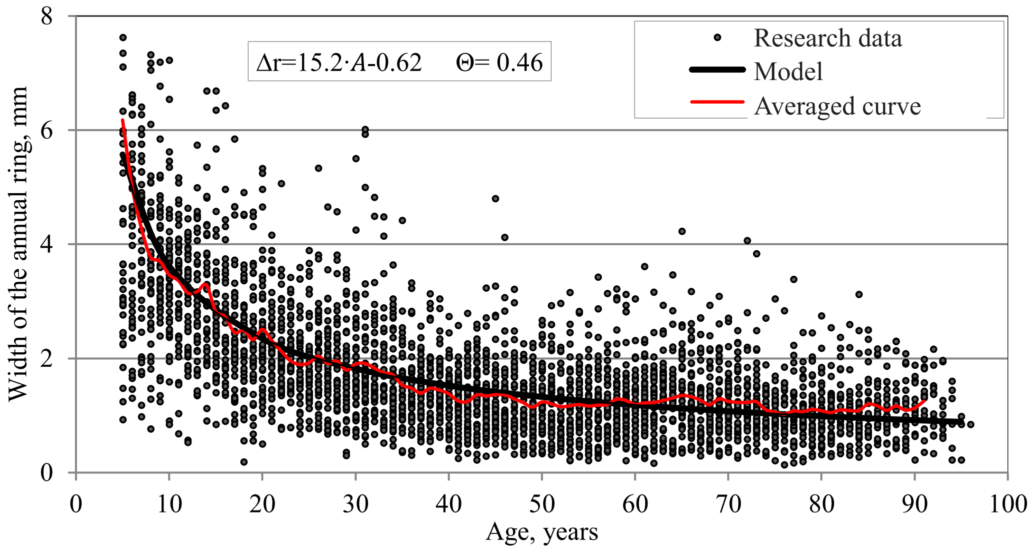

Figure 2. Dynamics of annual ring width of Scots pine trees

The adequacy of the developed mathematical model (2) with experimental data was verified as follows [17]:

$$\Theta = 1 - \frac{(\sum y - \tilde{Y})^2}{(\sum y - \bar{Y})^2} \qquad (2)$$

where Θ is the adequacy of the mathematical model; y are the factual values; $\tilde{Y}$ are the simulated values; $\bar{Y}$ is the arithmetic mean.

The developed mathematical model of the dynamics of the annual growth of trees' trunks (Δ_r) in pine stands adequately describes the established pattern.

Based on the data of annual radial increment of sample trees, the dynamics of DBH (Δd) with age (r=0.87) was established, and the corresponding mathematical model was developed (Fig. 3).

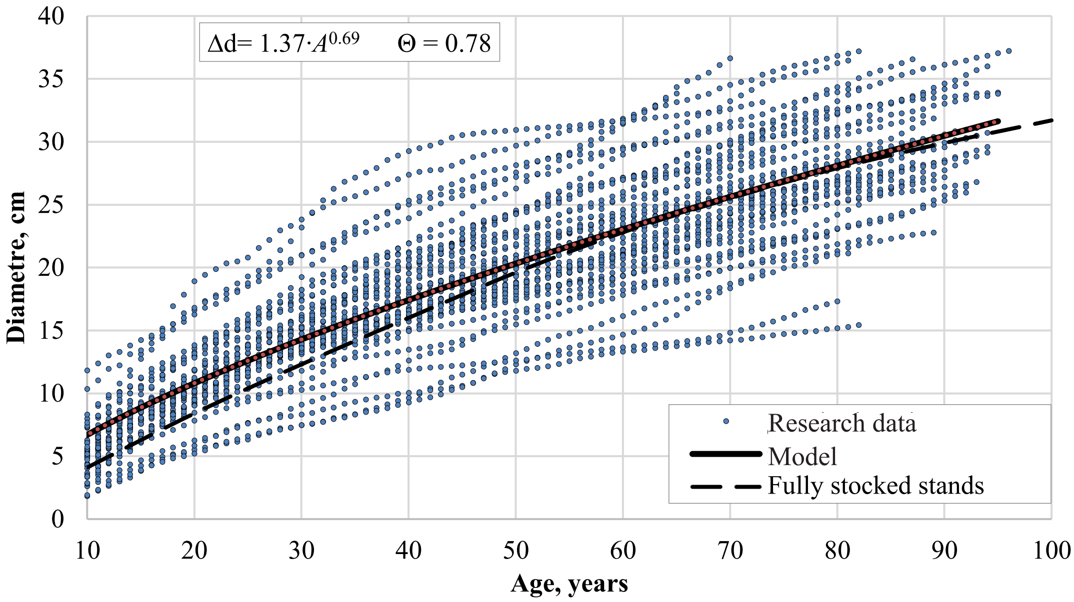

Figure 3. Dynamics of the diameter of Scots pine trees at a height of 1.3 m

The developed mathematical model of the dynamics of DBH (Δ_d) of trees in pine stands adequately describes the established pattern (Θ=0.78). For comparison, Figure 3 shows the dynamics of DBH of fully stocked (with a relative stocking of 1.0) artificial forests of the first (I) site index class [18]. The dynamics of the relative values of the current increment by diameter depending on age (r=-0.53) is established based on factual values and presented in Figure 4.

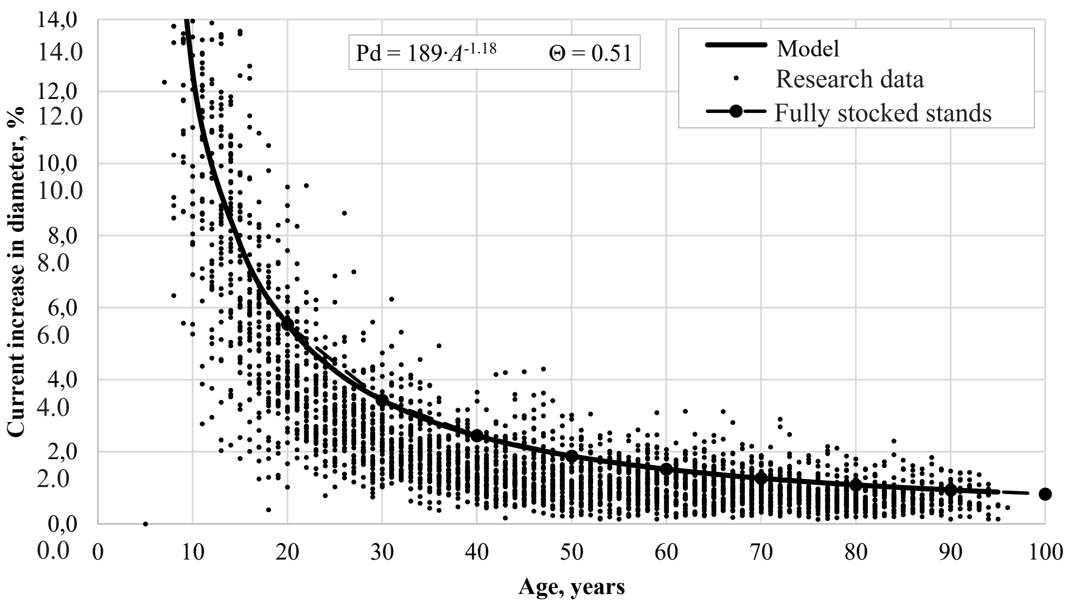

Figure 4. The dynamics of the relative values of the current increase in the diameter of Scots pine trees

The developed mathematical model (P_d) adequately describes the established pattern (Θ=0.51) and, in terms of the nature of the dynamics of changes in the current increment by diameter, is almost identical to fully stocked forests [18].

The study of the physiological stability of pine stands involved the standardisation of individual chronologies through the calculation of sensitivity coefficients ($K_{i(t)}$) as follows [1]:

$$K_{i(t)} = (R_{i(t)} - R_{i(t-1)})/(R_{i(t)} + R_{i(t-1)}) \quad (3)$$

where $R_{i(t)}$ is the current annual ring width, mm; $R_{i(t-1)}$ is the annual ring width a year ago, mm.

Sensitivity coefficients can vary from −1 to +1. In a steady state, the coefficients approach 0, and an increase in amplitude indicates a decrease in the stability of the stand and the emergence of the probability of exceeding a certain threshold level. Both sharp negative and positive values indicate a decrease in the stand stability (Fig. 5).

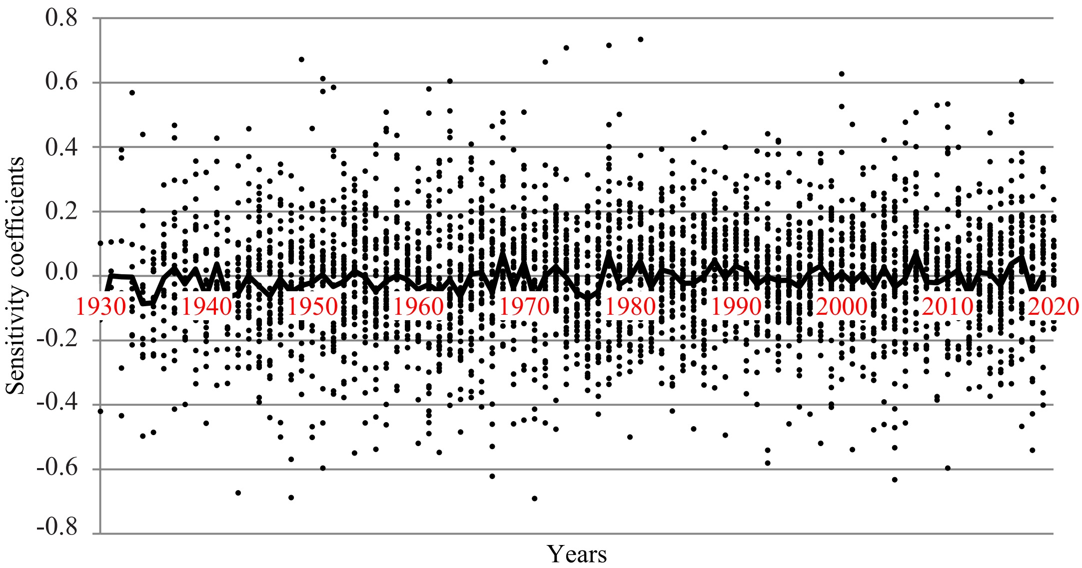

Figure 5. Physiological stability of Scots pine trees

Comparison of the obtained values of the sensitivity coefficients allows evaluating the specific features of the development of trees in the stand. The variation of sensitivity coefficients (Fig. 5) indicates the state of their natural stability in different age periods. No significant physiological reaction was found during the growth and development of Scots pine trees in Ukrainian Polissia. The research results suggest that the effect of short-term stress reactions on the state of physiological stability of pine stands is insignificant; they acquire maximum resistance to adverse environmental factors at the age of 50-60 years and older. A comparison of the results of the study of the physiological stability of pine stands with the data of other authors showed slight differences within the peak periods [1].

Conclusions

The data of the tree-ring chronology and the conducted correlation analysis showed that the pairwise correlation coefficients between the radial increment value and the current increment by diameter have an inverse relationship, and a direct relationship with DBH.

Mathematical modelling provided a model of the width dynamics of the annual ring depending on the age of trees, and the verification of the model proved its adequacy to the experimental data. The mathematical model of the dynamics of DBH of trees adequately describes the established pattern and has substantial differences compared to fully stocked forests, especially up to 60 years of age.

The developed mathematical model of the percentage dynamics in the current increment by diameter of modal (widespread) pine forests is almost identical to the dynamics of this indicator in fully stocked forests and adequately describes the experimental data.

The study of the physiological stability of trees in pine stands did not establish a significant physiological response to natural and climatic factors, and the impact of short-term stress reactions on the growth and development of pine stands in Ukrainian Polissia is insignificant.

At present, the question of finding innovative approaches to substantiating the volume of wood harvesting has matured in Ukraine. The results of this study can be used to further investigate the increment growth of pine stands by volume and develop corresponding recommendations.

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Ріст та фізіологічна стійкість соснових насаджень Українського Полісся

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Анотація. Обґрунтування обсягів використання лісових ресурсів, які б відповідали принципам стійкого ведення лісового господарства є основною передумовою проведення цього дослідження. Мета дослідження полягає у з'ясуванні особливостей росту соснових насаджень та їхньої фізіологічної реакції на несприятливі чинники. Дослідний матеріал (керни) був відібраний у соснових деревостанах Українського Полісся за допомогою приросного бура Haglöf на висоті стовбура дерева 1,3 м. Визначення кількості річних кілець та величини радіального приросту проводилось за допомогою програми ImageJ, що дозволило отримати деревно-кільцеву хронологію модельних дерев. Статистичний аналіз дослідних даних засвідчив, що мінливість радіального приросту з віком зменшується, а його величина знаходиться в межах від 0,99 до 2,78 мм. Середнє значення радіального приросту у досліджуваному масиві даних становить 1,79 мм. Середня кількість річних кілець дерев сосни звичайної (*Pinus sylvestris* L.) становить 80: мінімальна 61, максимальна 92. Проведений кореляційний аналіз дослідних даних засвідчив, що парні коефіцієнти кореляції радіального приросту (-0,54) та поточного приросту за діаметром (-0,53) з віком дерев мають обернений, а діаметра з віком – прямий зв'язок (0,87). Розроблені математичні моделі динаміки ширини річного кільця, діаметра стовбура дерева та поточного приросту за діаметром дозволяють оцінити особливості росту дерев сосни звичайної протягом усього життя. Проведено порівняння отриманих результатів із таблицями ходу росту повних (за відносної повноті 1,0) насаджень. Перевірка розроблених математичних моделей на адекватність засвідчила точність заданих закономірностей та є наступною: для динаміки ширини річного кільця становить 0,46; діаметра стовбурів дерев на висоті 1,3 м – 0,78 та відсотка поточного приросту за діаметром – 0,51. На основі стандартизації індивідуальних хронологій, шляхом розрахунків коефіцієнтів чутливості, не встановлено значної фізіологічної реакції. Відповідно вплив короткотривалих стресових реакцій є несуттєвим. Максимальна стійкість соснових насаджень до неспрятливих чинників середовища досягається у 50-60 річному віці. Дослідження є важливим для оцінювання впливу кліматичних змін та інших несприятливих факторів на ріст соснових насаджень і прогнозування динаміки таксаційних показників. Отримані результати можуть бути використані спеціалістами ВО «Укрдержліспроект» при актуалізації таксаційних показників і обґрунтуванні обсягів використання лісових ресурсів.

Ключові слова: сосна звичайна, деревно-кільцева хронологія, коефіцієнти чутливості, поточний приріст за діаметром, радіальний приріст

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Use of Dead Oak Wood in Furniture Products

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Abstract. Today, furniture made of wood, on which the openings of insect passageways are visible, is popular. Artificially creating such holes on healthy wood does not meet the aesthetic needs of consumers. Considering the annual increase of 8-10 thousand hectares in drying oak stands in Ukraine and, accordingly, the cost of deadwood reduced by almost 50%, it is proposed to use it after proper treatment to destroy pests for the manufacture of furniture products. An analysis of wood disinfection methods was carried out, which transformed over time from non-toxic substances and processing methods – oil, tar, resin, storage in salt water, charring to modern ones using harmful chemical compounds – pentachlorophenol, alkaline chloride, sodium fluorosilicates, tars, DDT, etc. Analysis of available methods for exterminating timber pests allowed distinguishing antiseptics, fumigation, ultra-high frequency current treatment and thermal modification. The purpose of this study was to determine the method of disinfection of sawn goods made from deadwood oak for further use in furniture products. Theoretical and experimental methods were used to achieve this purpose. The scientific originality of this study lies in the application of the fuzzy logic method to select the priority method of wood disinfection, which lies in decomposition of the problem into simpler components and step-by-step prioritisation of the evaluated components using paired comparisons. For alternative options to achieve the purpose, the following criteria were applied: efficiency, environmental friendliness, industrial manufacturability, durability of the result. The corresponding calculations performed, confirmed by the required consistency index, showed the priority of the method of thermal modification of wood. Experimental studies of heat treatment with the proposed modes of deadwood oak with existing pests, namely Xyleborus dispar (*Xyleborus dispar*), were carried out. The study determined the possibility of using the action of hot temperatures (t>110°C) for complete sterilisation of deadwood oak. The result of practical application of this eco-safe method for the manufacture of tabletops has shown its effectiveness and can be useful for furniture makers

Keywords: pests, disinfection methods, thermal modification, thermomodified wood tabletop

Introduction

Modern designers try to bring naturalness and environmental friendliness to the interior, while solid wood still is the always used material. In the modern-day European furniture market, there is a considerable demand for "vintage" furniture, which shows the holes of insect passages [1]. Tables made of deadwood oak affected by timber pests are popular for use both in the interiors of private and public premises, as well as in the open air [2]. The presence of insects in deadwood can be traced by the presence of powder on the surface of wood, which is a product of the vital activity of not only mature pests, but also deposited pupae. Despite this, such wood has an advantage since the price for it is almost 2 times less than for healthy wood [3]. This is relevant for Ukraine, as the volume of deadwood has considerably increased, and over the past 7-8 years it has grown from 8% to 18%. Today, drying covers an area of forests of more than 35 thousand hectares [4]. The cause of drying out of forests can be damage by timber pests that weaken the wood.

Usually, insects affect the sapwood part of tree species. They attack construction wood, lumber, and furniture.

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Adult insects have a length of 2.5 to 5.0 mm. Their shapes are usually elongated and cylindrical, and their colour ranges from reddish-brown to deep brown or black. Their life cycle averages 1-3 years, but females lay their eggs in wood. Larvae form tunnels in both conifers and hardwoods. They can digest cellulose and hemicellulose and break down cell wall carbohydrates, starch, and sugars in the cell contents [5; 6]. The result of their activity is the gradual loss of wood's physical and mechanical properties, which considerably reduces the possibility of using it for products used both outdoors and in internal house structures, etc. It also significantly reduces the time of use of wood products [7].

Organisms (fungi, insects) that destroy wood have been with humanity for many years and have caused great disasters, so finding ways to get rid of them has always been natural. The first chemical conservation measures included cleaning with oil, tar, or resin, storage in salt water, charring, etc. [7]. Later, they began to use pentachlorophenol, alkaline chloride, sodium fluorosilicates, boric acid, potassium dichromate, sodium dichromate, tars, DDT, gaseous pesticides (fumigants, for example, bromomethane and monophosphane) and others [7-9]. However, some of them (pentachlorophenol, alkali chloride, sodium fluorosilicates, DDT, gaseous pesticides, etc.) were banned for use due to health concerns [8].

Today, the most common methods of sterilisation are steam treatment, gamma radiation, and ultra-high frequency current, which are recommended by the European standards EN 113-1 (2021) [10] and EN 113-2 (2021) [11]. The use of gamma radiation, despite the positive effect, requires the use of expensive equipment – a neutron accelerator. Microwave insecticide is also costly, being used for disinfection of finished wood products during restoration [12; 13].

Thermal sterilisation is used worldwide and is currently the most practical and environmentally friendly treatment for pest control in solid wood. The international phytosanitary standard for wood packaging material requires heating the wood to t=56°C for at least 30 minutes. For complete sterilisation of wood, higher temperatures are used – t>110°C [14].

Heat treatment of wood has become quite popular over the past twenty years [15], although it is still being developed as an industrial process to improve some wood properties (shape stability, durability, light sensitivity, etc.). The first heat treatment studies concerned the determination of equilibrium humidity, dimensional stability, durability, and mechanical properties [16]. In the future, a decrease in weight, hygroscopicity, colour change over the cross-section were identified [17; 18], chemical transformations of the wood structure, and an increase in its biological stability [19; 20]. This has encouraged the use of thermally modified wood in non-structural products that can be used outdoors or in products that come into contact with water, such as sinks, bathtubs, and kitchen tabletops [21; 22].

In Ukraine, the following methods are mainly used for pest control: fumigation, antiseptics, which involve toxic substances that are harmful not only to insects, but also to processing personnel, and possibly to users of products treated in this way [23]. For local extermination of insects in finished products, a microwave insecticide is used that generates ultra-high frequency current (microwave) [23]. In case of preparing wood raw materials for the manufacture of furniture, the use of the above methods is questionable, since its manufacturability is complicated, and therefore it is relevant to determine the method of wood disinfection that is harmless to manufacturers and consumers.

The purpose of this study was to determine a rational way to exterminate pests in sawn timbers made from deadwood oak.

Materials and Methods

Among the common methods of pest control in Ukraine, it was necessary to choose a priority one. For this purpose, one of the methods of fuzzy logic is used – the hierarchy analysis method (HAM), which lies in decomposing the problem into simpler components and gradually prioritising the evaluated components using paired comparisons [24].

The application of HAM includes defining the purpose, alternative options for achieving the purpose, and criteria for evaluating the quality of alternatives. In the case under study, the purpose is to choose a priority method of wood disinfection; the following methods of disinfection are chosen as alternatives: A_1 – fumigation, A_2 – antiseptic, A_3 – microwave exposure, and A_4 – thermal modification of wood (TMW); as criteria: Cr_1 – efficiency, Cr_2 – environmental friendliness, Cr_3 – industrial manufacturability, Cr_4 – durability of the result.

After determining the priorities of all elements of the hierarchy using the method of paired comparisons using the Saati scale [25] and synthesising global priorities of alternatives, by linear convolution of priorities of elements and hierarchies, judgments are verified for consistency and decisions are made based on the results obtained. In this case, the matrix of paired comparisons (MPC) of criteria is built relative to the purpose, and the MPC of alternatives will be relative to each criterion. In the case under study, there were four MPC alternatives.

The geometric average is calculated for each matrix, G_i, and local priority, LPr_n, for each row of the matrix:

$$G_i(a_{i1}, a_{i2}, \dots a_{is}) = (a_{i1} * a_{i2} * \dots * a_{is})^{\frac{1}{s}} \quad (1)$$

where *i* is the matrix row number; *s* is the number of elements in the i^{th} row of the matrix;

$$a_{i1} = w_1/w_1;\ a_{i2} = w_1/w2;\ \dots\ a_{is} = w_1/w_s \quad (2)$$

w is the accepted numerical value on the Saati scale.

$$LP_{r_n} = \frac{[(w_n/w_1)(w_n/w_2)\dots(w_n/w_n)]}{(G_1 + G_2 + \dots + G_n)} \quad (3)$$

where *n* is the row number of the MPC.

To control the consistency of expert assessments, two related characteristics were used – the consistency index (CI) and the consistency ratio (CR):

$$CI = \frac{\lambda_{max}}{m - 1} \quad (4)$$

$$CR = \frac{CI}{P_m} \quad (5)$$

where *m* is the matrix size; P_m is the CI for a positive inverse symmetric matrix of random size estimates *m x m*; λ_{max} is the maximum eigenvalue of MPC:

$$\lambda \sum a_{1i_1} \sum a_{2i_2} \sum a_{ni_{n_{max}}} \quad (6)$$

where $\sum a_{1i}$ is the sum of the values of the first column of the MPC; is the local priority value of the first line of the MPC.

At *CR*<0.1 ... 0.2, the calculations performed are considered satisfactory.

The solution of the multi-criteria ranking problem is presented in the form of a global priority vector (GlPr) of alternatives in relation to the purpose. The GlPr is calculated as follows: each component of this vector constitutes a scalar product of the local priority vector (LPr) of criteria and a vector comprising local priorities of the alternative to the presented criteria. The largest value of the GlPr vector corresponds to the priority alternative.

For experimental studies, samples of deadwood oak were selected, with signs of the presence of pests – white powder on the surface of boards and insect passages visible to the naked eye (Fig. 1).

Figure 1. Biological damage to samples

It was found that along the entire length of the lumber there were areas of settlement of timber pests. The samples of lumber under study can be attributed to "old deadwood". Their sapwood part was at the last stage of biological destruction.

To detect the presence of pests in the samples, one of them was split. The resulting sample particles were placed in a microscope Micromed XS 330 microscope with 240x and 1600x magnification – Figure 2. This allowed detecting the insect passages within the wood – Figure 3.

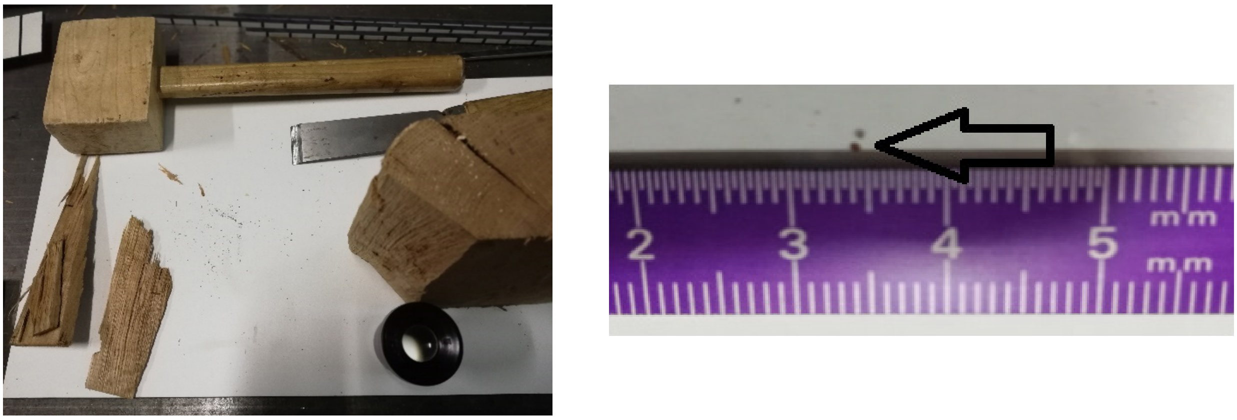

Figure 2. Shredding for the study of biological damage to pieces of lumber and the separation of existing pests

Figure 3. Timber pest passages within the wood

Samples of affected wood were dried in a laboratory convection drying chamber at t=50°C to a final wood moisture content of W=8%. Subsequently, they were placed in a laboratory thermal chamber, where they were treated with the following schedules – Table 1. The applied processing temperature parameters are consistent with those accepted in industry [15]. A total of 81 samples were examined.

Test samples of oak wood were made from sawn timber from a round log in the Zhytomyr region and had dimensions of 50 x 180 x 200 mm.

Table 1. Schedules parameters of thermal modification of oak wood samples

Schedules number	Processing temperature, °C	Temperature exposure time, h		
		6	12	24
1	110	9 samples	9 samples	9 samples
2	160	9 samples	9 samples	9 samples
3	220	9 samples	9 samples	9 samples

Results and Discussion

It was established that a *Xyleborus dispar* was present in the oak wood during the initial settlement. This is evidenced by the oblong shape of the horizontal entrance channels in the wood, which have a depth of about 5 centimeters and have branches for uterine passages (Fig. 4.) extending inside the wood. Furthermore, the presence of darkening of the passages was detected and this is also an inherent feature of this type of pest.

Figure 4. Place of pupation during the pest

Other insect species were also found in the wormholes of the samples. These were entomophages, mites that feed on larvae and pupae of *Xyleborus dispar* (Fig. 5).

According to the calculation performed for (1-6), a matrix of priorities of criteria relative to the purpose and alternatives relative to each of the criteria is constructed using HAM – Table 2.

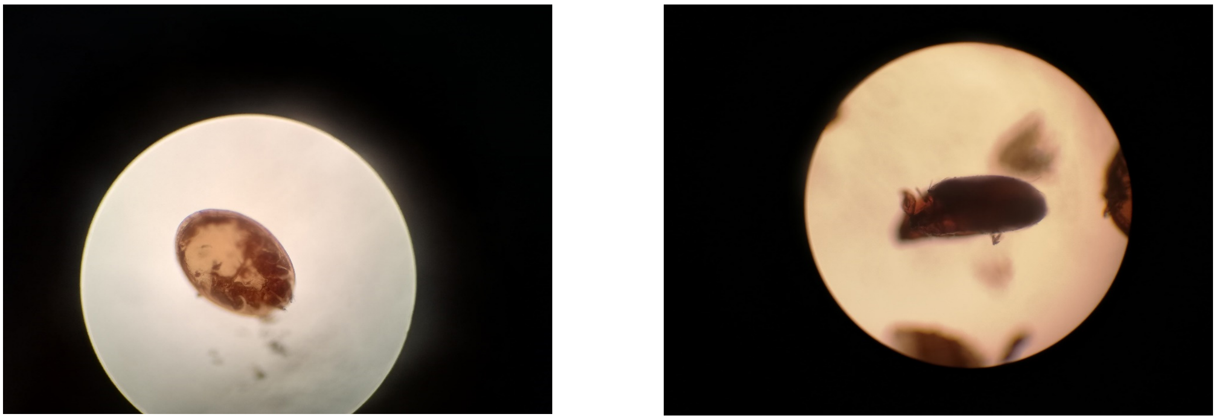

Figure 5. Entomophages found in wood

Table 2. Matrix of priorities criteria relative to the purpose and alternatives for each criterion

Criteria	Criterion priority	Alternatives			
		A_1	A_2	A_3	A_4
Cr_1	0.038	0.090	0.094	0.069	0.059
Cr_2	0.086	0.121	0.136	0.112	0.055
Cr_3	0.099	0.204	0.186	0.325	0.173
Cr_4	0.777	0.585	0.584	0.494	0.713
Consistency of calculations					
	0.095	0.024	0.191	0.071	0.174

The calculation results are clearly consistent since they are within the required limits of *CR*<0.1 ... 0.2. The results of determining the global priority method of wood disinfection from the accepted alternatives are presented in Table 3.

Table 3. Global priorities of accepted alternatives

Alternatives	A_1	A_2	A_3	A_4
GlPr	0.489	0.488	0.428	0.578

Therefore, the greatest priority is given to Alternative 4 – thermal treatment of wood, so in experimental studies, the TMW method was used to destroy pests.

As a result of thermal modification of oak wood samples affected by *Xyleborus dispar*, all samples were found to have darkened. This is the result of the decomposition of hemicellulose and lignin [26].

Heat treatment of wood affects the viability of insects, coagulation (denaturation) of proteins essential for the existence of insects occurs. Increase in wood temperature up to t=110°C and above caused the death of the *Xyleborus dispar* beetle at all stages, namely eggs, larvae, pupae, adult insects due to the destruction of the protein inherent in the body [26; 27]. In the case of the presence of other pests in the firewood of both deciduous and coniferous species, namely weevils, bark beetles, etc., according to [28], treatment at t=60°C for 60 minutes was sufficient [29]. However, the use of t⩽110°C prevents the decomposition of pest-friendly components of the wood structure – hemicellulose, which does not guarantee the viability and reproduction of newly populated pests.

The remains of *Xyleborus dispar* that were detected after thermal treatment with schedules 1 (24 hours) and 2 (12 hours and 24 hours) are presented in Figure 6.

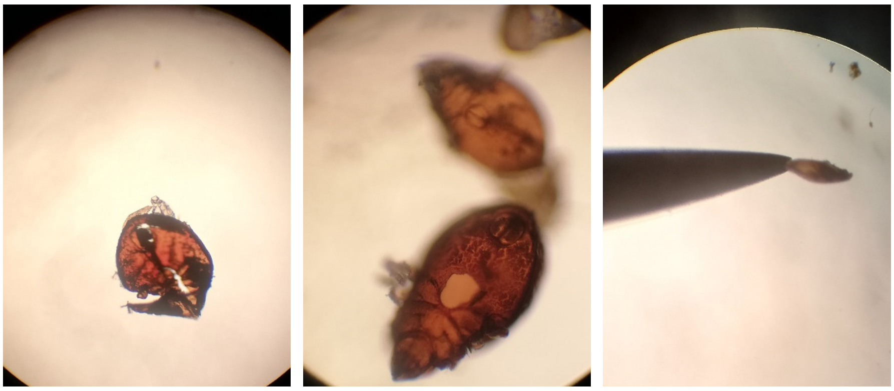

Figure 6. Insect remains found in oak samples after TMW

No insect remains were found in samples treated with schedule 1 (6 h and 12 h) and mode 2 (6 h). The samples treated at t=220°C were charred, and therefore were not examined under a microscope for the presence of insect remains. Moreover, such wood can no longer be used for making furniture. The results obtained indicate that thermal modification of sawn timber from deadwood oak, which is affected by the *Xyleborus dispar*, promotes the extermination of insects. Due to the destruction of hemicellulose at t>110°C, which is a nutrient for insects, products made of thermal-treated wood will not be attractive to pests during operation [20]. Several tables were made from the oak lumber selected for the study in 2019 (Fig. 7).

a) b)

Figure 7. Table made of thermally modified oak wood: a – part of the tabletop that shows the passages of insects; b – general view of the table

These products have been used for almost three years in the open air. During this time, no signs of insect activity were detected, i.e., the presence of powder. Furthermore, the products did not change their shape as a result of both dripping moisture and environmental climate changes. Thus, thermal modification of wood can be recommended for disinfection of deadwood by pests for the manufacture of such modern popular antique furniture.

Conclusions

1. An increase in the amount of deadwood oak affected by pests limits its full use for the manufacture of furniture products. In the wood of ordinary oak originating from the Zhytomyr region, the presence of a slight destruction of the core part formed by the passages of the timber pest – the *Xyleborus dispar* – was revealed.

2. The analysis of methods of wood disinfection allowed identifying the methods common in Ukraine – fumigation, antiseptics, ultra-high frequency current treatment, thermal modification. Using the hierarchy analysis method, an effective ecological method was chosen for the selected methods of pest control – thermal modification of wood, which has successful industrial use.

3. Experimental studies of the influence of the proposed schedule parameters of thermal treatment on the viability of pests proved the possibility of its further use in popular furniture products made of oak wood, which have signs of ageing, but will not be destroyed over time.

4. For the possibility of using disinfected dead-wood thermally modified oak wood in other furniture products, it is necessary to conduct studies of its mechanical properties.

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Використання сухостійної деревини дубу у меблевих виробах

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Анотація. Сьогодні популярними є меблі, виготовлені із деревини, на яких видно отвори ходів комах. Штучне створення таких отворів на здоровій деревині не задовольняє естетичних потреб споживачів. Враховуючи щорічне зростання на 8–10 тис. га в Україні площі деревостанів дубу, що висихає та, відповідно, знижену майже на 50 % вартість сухостійної деревини запропоновано використання її після відповідного оброблення по знищенню шкідників для виготовлення меблевих виробів. Проведено аналіз способів знезараження деревини, які трансформувалися із часом від досить нетоксичних речовин та способів обробки – олії, дьогтю, смоли, зберігання в солоній воді, обвуглювання до сучасних із використанням шкідливих хімічних сполук – пентахлорфенолу, лужного хлориду, натрію фторосилікатів, гудронів, ДДТ тощо. Аналіз доступних способів ліквідації стовбурових шкідників, дозволив виділити антисептування, фумігацію, оброблення струмом надвисокої частоти та термічне модифікування. Метою дослідження є визначення способу знезараження пилопродукції із сухостійної деревини дубу для подальшого використання у меблевих виробах. Для досягнення означеної мети застосовано теоретичний та експериментальний методи. Наукова новизна полягає у застосуванні методу нечіткої логіки для вибору пріоритетного способу знезараження деревини, який полягає у декомпозиції проблеми на більш прості складові частини і поетапному встановленні пріоритетів оцінюваних компонентів з використанням парних порівнянь. Для альтернативних варіантів досягнення цілі були застосовані такі критерії – ефективність, екологічність, промислова технологічність, довговічність результату. Проведені відповідні розрахунки, що підтверджені необхідним індексом узгодженості, показали пріоритет способу термічного модифікування деревини. Проведено експериментальні дослідження термічного оброблення запропонованими режимами сухостійної деревини дубу з наявними шкідниками, а саме непарного західного короїду (*Xyleborus dispar*). Визначено можливість використання дії високих температур (t>110 °C) для повної стерилізації сухостійної деревини дубу. Результат практичного застосування цього еколого безпечного способу для виготовлення стільниць показав його ефективність і може бути корисним для меблевиків

Ключові слова: шкідники, способи знезараження, термічне модифікування, стільниця з термомодифікованої деревини

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Biotechnological Aspects of Propagation of Black Poplar Hybrids "San Giorgio" and "Ghoy"

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Abstract. Energy independence of the country can be solved in several ways. One of them is the creation of energy plantations of woody plants. The area increase of such plantations is limited by the insufficient amount of high-quality planting material. Hybrid plants of the genus *Populus* are of considerable interest when creating plantations. Given that not all hybrids are successfully propagated by conventional vegetative methods, the use of biotechnological methods, namely microclonal propagation, solves the mentioned problem. This method allows obtaining a large amount of high-quality, uniform planting material. The purpose of this study was to develop the technology of microclonal propagation of black poplar hybrids *'San Giorgio'* and '*Ghoy*'. The study used generally accepted biotechnological methods in the author's modification at all stages of obtaining planting material of regenerating plants of poplar hybrids. Studies have established a positive effect when obtaining an aseptic culture of sterilising substances 0.1% $AgNO_3$, 2.5 and 1.25% NaClO, 0.05% sodium merthiolate and 0.1% $HgCl_2$. The largest number of aseptic viable explants was obtained by cultures using a 0.05% solution of sodium merthiolate after exposure for 5 and 10 minutes. When rooting microshoots on a hormone-free nutrient medium ½ MS and with the addition of 0.1-1.0 mg/l IBA, it was established that the best parameters for rooting microshoots are on a hormone-free nutrient medium ½ MS. Adaptation was carried out for 4 weeks in a greenhouse on a substrate that included components of peat:sand:perlite in a ratio of 1:1:1. The viability of regenerating plants of black poplar hybrids '*San Giorgio*' and '*Ghoy*' was more than 91%. The conducted research and the obtained results will be useful for producers of planting material and the scientific environment, which develop renewable energy sources through the creation of energy plantations of fast-growing woody plants

Keywords: explant, nutrient medium, phytohormones, substrate, planting material, *in vitro*

Introduction

Global threats associated with climate change and military aggression adversely impact the development of food and energy security in most countries of the world. This is primarily due to their dependence on oil, natural gas, and food exporting countries. In modern Ukrainian realities, the issues of energy independence and the introduction of national energy-efficient technologies are also of particular importance [1-3].

One of the solutions to Ukraine's energy security is the creation and operation of energy tree plantations. The rather slow implementation of the modern transformational approach to the creation of renewable forest resources in the Ukrainian forestry practice is explained, among other things, by the insufficient production of planting material for the creation of energy plantations. For this purpose, as the long-term experience of foresters in Italy, France, Slovakia, Hungary, and many other countries of the world shows, it is better to use planting material of hybrids of fast-growing tree species, namely the genus *Populus* [4-6]. The simultaneous use of conventional and modern methods of plant propagation allows obtaining a large amount of planting material and fully meeting the needs for it to create energy plantations. The use of a certain method of obtaining planting material is determined by the characteristics of hybrids, since they cannot always be propagated by conventional vegetative methods. In this case, as practice

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shows, it is better to use biotechnological methods, namely microclonal propagation [7-9].

Literature Review

O. Yu. Chornobrov used fragments of microshoots with one bud and leaf plates as initial explants when developing the technology of micropropagation of poplar hybrids. Effective sterilisation of shoot fragments of cultivars P. × *canadensis* 'Robusta' and P. × *canadensis* 'Dorskamp' was achieved by applying 0.1% $HgCl_2$ for 10-12 minutes. For microshoots of cultivars P. × *canadensis* 'Tardif de Champagne', P. × *canadensis* 'I-45/51' and P. × *canadensis* 'Blanc du Poitou', exposure to 2.5% NaClO for 8-10 min followed by transfer in 1.0% $AgNO_3$ was optimal. The formation of microshoots by direct morphogenesis in the tissues of the leaf blades of plants of the hybrids P. × *canadensis* 'I-45/51', P. × *canadensis* 'Tardif de Champadne', P. × *canadensis* 'Robusta', P. × canadensis 'Dorskamp' was recorded on the nutrient Murashige and Skoog (MS) medium [10] with 1.0 mg/l BAP (N^6 – benzylaminopurine) and 0.5 mg/l NAA (α-Naphthaleneacetic acid) under illumination of 2.0-3.0 klx. Actively growing microshoots of stem-derived plants of hybrid P. × *canadensis* 'Tardif de Champadne' were obtained on MS with the addition of 0.1 mg/l BAP and 1.0 mg/l IAA (β-indolyl-3-acetic acid) and 7.5 g/l of glucose [11].

Upon developing approaches to microclonal reproduction of the green-barked form of aspen (*Populus tremula* L.), S.Yu. Bilous established the need for individual selection of nutrient medium for cultivation of different types of explants at each subsequent stage of microclonal reproduction. It was determined that the best option is a nutrient medium with the following composition: 0.5 mg/l TDZ (thidiazuron) + 1 g/l activated carbon and 0.25 mg/l kinetin 1 + 1 g/l activated carbon, which ensure the realisation of not only the induction of organogenesis, but also the morphogenetic potential of the explant with the formation of rooted plants [12].

Chinese scientists have developed a step-by-step micropropagation technology of regenerating Ussuri poplar plants. Cultivation of buds was carried out on nutrient medium for woody plants (WPM) [13] with the addition of different concentrations of BAP, IBA (3-Indolebutyric acid) and TDZ. The formation of microshoots from buds ranged within 75.2-78.0%. Rooting of microshoots took place within a week on MS nutrient medium, with the content of macro- and micro-salts reduced by half. Regenerating plants were adapted for 4 weeks on a substrate comprising such components as earth:vermiculite:perlite. Subsequently, the containers with regenerating plants were moved to the landfill [8].

Lithuanian researchers developed an alternative approach to the micropropagation of the hybrid (*Populus alba* L. × *P. tremula* L.), which was based on limiting the gas exchange between the internal and external environment of the culture vessel, and not on the application of exogenous hormones. Explants, apical and internodal parts of shoots were cultivated in sealed (stoppered Paratilm) or unstoppered glass culture tubes on hormone-free nutrient medium WPM. Proliferation of microshoots on apical explants was observed in closed culture tubes, but not in unstoppered ones. The difference between the two variants increased over time in the number of microshoots and became threefold after three months of cultivation. Shoots taken from stoppered culture tubes could be distinguished by longer shoot length compared to shoots from unstoppered tubes during the next stage of cultivation under the same conditions [14]. When developing the technology of microclonal propagation, researchers consider the specific features of propagated plants and apply generally accepted biotechnological methods in the author's modification: starting from the selection of explants from mother plants, ending with the adaptation of regenerating plants to environmental conditions.

Considering the need for continuous improvement of technological processes of microclonal reproduction while taking into account the local factors that determine the success of obtaining planting material, the purpose of this study was to improve the technology of micropropagation of black poplar hybrids *'San Giorgio*' and '*Ghoy*', as promising species for the creation of energy plantations.

The originality of this study lies in the optimisation of the process of obtaining regenerating plants of black poplar hybrids *'San Giorgio*' and '*Ghoy*'.

Materials and Methods

Parts of one-year shoots 10-25 cm long were used to select initial explants. Donor plants of black poplar hybrids '*San Giorgio*' and '*Ghoy*' are located at the poplar mother plantation of the educational and research nursery of the Department of Forest Restoration and Melioration of the National University of Life and Environmental Sciences of Ukraine. Dormant and germinated buds were used as initial explants for introduction into *in vitro* culture.

During the development of stepwise sterilisation of intact plants, the following sterilising substances were used for different exposure times: 0.1% solution of silver nitrate ($AgNO_3$), 2.5 and 1.25% solution of sodium hypochlorite (NaClO), 0.05% solution of sodium merthiolate and 0 .1% mercury chloride ($HgCl_2$).

Aseptic and viable explants were cultivated on a nutrient medium according to the MS prescription with a halved content of macro- and microsalts (½ MS) and the addition of 0.05-1.0 mg/l IAA, IBA, BAP and kinetin (6-(Furfurylamino)purine).

The obtained microshoots were rooted on ½ MS nutrient medium without growth regulators and with 0.1-1.0 mg/l IBA. Cultivation conditions: illumination 2.0-3.0 klx, photoperiod 16 h, temperature 24±1 °C, humidity 70%.

Adaptation to closed soil and substrate conditions was carried out in a greenhouse using a substrate consisting of components of peat:sand:perlite in a ratio of 1:1:1. Adaptation took place for 4 weeks in a greenhouse at 24±1 °C and a humidity of 80%.

Results and Discussion

The development of the technology for growing planting material of regenerating plants started with the acquisition of a well-growing aseptic culture. At this stage, a scheme for step-by-step sterilisation of the original explants with the selection of sterilising substances, their concentration, and exposure time is developed. The main task is to obtain aseptic, viable explants for further micropropagation.

Analysing the number of aseptic and viable explants after the use of sterilising substances, it was established that sodium hypochlorite and mercuric chloride are the least effective (Table 1). When using solutions of 1.25% and 2.5% sodium hypochlorite, aseptic explants were obtained in the black poplar hybrid '*San Giorgio*' from 53% to 89%, in

'*Ghoy*' – from 76% to 95%. But in the future, the number of viable explants substantially decreases, which is due to the toxicity of this solution. At the same time, a feature of the '*San Giorgio*' hybrid was its insensitivity to different concentrations of sodium hypochlorite solutions and exposure time for obtaining viable explants.

Table 1. Sterilisation efficiency of explants of black poplar hybrids '*San Giorgio*' and '*Ghoy*'

No.	Name of the sterilising agent and concentration	Exposure, min	Aseptic explants, %		Viable explants, %	
			San Giorgio	*Ghoy*	*San Giorgio*	*Ghoy*
1	0.1% mercury chloride ($HgCl_2$)	5	67±0.5	99±0.4	38±0.6	47±0.4
2	0.1 % mercury chloride ($HgCl_2$)	10	61±0.5	82±0.5	21±0.5	28±0.4
3	2.5% sodium hypochlorite (NaClO) solution	10	85±0.3	90±0.6	–	36±0.4
4	2.5% sodium hypochlorite (NaClO) solution	15	89±0.6	95±0.5	–	41±0.4
5	1.25% sodium hypochlorite (NaClO) solution	10	53±0.3	76±0.4	–	32±0.3
6	1.25% sodium hypochlorite (NaClO) solution	15	78±0.5	87±0.6	–	40±0.4
7	0.05% sodium mertiolate solution	5	92±0.4	93±0.5	83±0.5	85±0.6
8	0.05% sodium mertiolate solution	10	97±0.4	99±0.5	92±0.4	95±0.5
9	0.1% silver nitric acid solution	5	93±0.6	98±0.4	44±0.5	55±0.4
10	0.1% silver nitric acid solution	10	88±0.5	90±0.3	33±0.6	32±0.5

Due to the influence of the concentration of sterilising substances and exposure time, a positive effect on obtaining aseptic explants was found: in the hybrid '*San Giorgio*' – from 53% to 97%, and in the hybrid '*Ghoy*' – from 76% to 99%. Notably, increasing the time of exposure to the 0.1% silver nitrate solution and 0.1% mercuric chloride led to a substantial decrease in the number of aseptic and viable explants.

The study discovered the effective production of an aseptic culture using a 0.05% solution of sodium merthiolate with exposure for 5 and 10 minutes. Increasing the exposure time from 5 to 10 min positively influenced the increase of aseptic and viable explants: from 92% to 97% aseptic and 83% to 92% viable explants of the '*San Giorgio*' hybrid, from 93% to 99% aseptic and from 85% to 95% viable explants of '*Ghoy*' hybrid.

Other researchers also found a specific reaction of explants to the concentration of the sterilising substance and exposure time depending on the poplar hybrid upon obtaining an aseptic culture of poplar hybrids [11].

Based on the conducted research on obtaining an aseptic culture of poplar hybrids '*San Giorgio*' and '*Ghoy*', an effective method of sterilisation of the original explants has been developed, which is successful from the standpoint of introduction into culture *in vitro*.

After 6-7 days, aseptic viable explants were transferred to ½ MS nutrient medium with growth regulators IAA, IBA, BAP, and kinetin at a concentration of 0.05-1.0 mg/l (Table 2).

Table 2. Dependence of the formation of microshoots on the concentration of growth regulators

Modification of the nutrient medium	Name of the growth regulator	Concentration, mg/l	The number of explants that formed microshoots, %		Height of microshoots, cm	
			San Giorgio	Ghoy	San Giorgio	Ghoy
1	IAA	0.05	21±0.3	22±0.4	2.0±0.22	2.1±0.25
2		0.1	18±0.4	17±0.5	1.7±0.26	1.8±0.27
3		0.2	13±0.5	12±0.4	1.5±0.21	1.7±0.24
4	IBA	0.05	36±0.4	36±0.5	1.9±0.25	2.0±0.24
5		0.1	24±0.5	25±0.5	1.7±0.25	1.9±0.25
6		0.2	18±0.7	19±0.6	1.5±0.26	1.6±0.23
7	BAP	0.25	86±0.3	85±0.4	4.3±0.21	4.5±0.19
8		0.5	77±0.4	79±0.5	4.0±0.19	4.1±0.21
9		1.0	74±0.5	75±0.6	3.8±0.22	4.0±0.19
10	kinetin	0.25	63±0.4	65±0.4	3.7±0.20	3.9±0.22
11		0.5	60±0.3	62±0.6	3.1±0.22	3.3±0.20
12		1.0	49±0.6	48±0.7	3.0±0.19	3.2±0.21

The use of IAA and IBA in low concentrations in the nutrient medium showed a weak stimulating effect on the formation of microshoots of poplar hybrids. Due to their action, the emergence of microclones was observed in up to 36% of explants. The formed microshoots were thin and often vitrified, while their growth took place. The results upon using indolylbutyric acid turned out to be better than upon using indolylacetic acid.

When the concentration of growth regulators of the auxin group increased to 0.2 ml/l, the formation of lignified, hard, non-morphogenic callus and weak roots, which were unsuitable for further adaptation, was observed.

Proceeding from the obtained data, the addition of IAA and IBA to the nutrient medium for the multiplication of microshoots, regardless of the concentration of auxins, did not give the expected result. The use of these growth regulators for the formation of microclones of black poplar hybrids ‘*San Giorgio*’ and ‘*Ghoy*’ can be considered ineffective.

Compared to auxins, cytokines BAP and kinetin showed more intense shoot formation when added to the nutrient medium. Notably, the inclusion of BAP in the nutrient medium in all variants, compared to kinetin, caused intensive formation of microshoots from 75% to 85%, depending on the concentration. Therewith, the best stimulation of the emergence of microshoots (85%) occurred on the nutrient medium with 0.25 mg/l BAP. Microshoots of poplar hybrids ‘*San Giorgio*’ and ‘*Ghoy*’ obtained on nutrient medium ½ MS + 0.25 mg/l BAP also prevailed in height compared to all other options (Fig. 1).

Figure 1. General appearance of microshoots of black poplar hybrids ‘*San Giorgio*’ and ‘*Ghoy*’ on nutrient medium ½ MS + 0.25 mg/l BAP

In studies [8; 15], which covered the microclonal propagation of poplar hybrids, intensive formation of microshoots was also obtained with the content of cytokine group growth regulators in the nutrient medium. This is because cytokinins contribute to the elongation of cells and the formation of explant tissues, which further affects the formation of mesenteries and the growth of the stem. They also positively affect the induction of adventitious buds. Microshoots were rooted on a hormone-free ½ MS medium and with 0.1-1.0 mg/l IBA to the nutrient medium (Table 3).

Table 3. Specific features of rooting poplar hybrids ‘*San Giorgio*’ and ‘*Ghoy*’

Modification of the nutrient medium	IBA concentration, mg/l	% of rooted microshoots	The average number of roots, pcs.
1	–	92±0.3	2.5±0.18
2	0.1	92±0.5	1.9±0.25
3	0.5	93±0.6	2.2±0.21
4	1.0	94±0.7	2.4±0.24

As the above data shows, there were 92% of rooted microshoots on a hormone-free nutrient medium ½ MS (Fig. 2). The addition of IBA slightly increased the percentage of rooted microshoots by 1% and 2% at concentrations of 0.5 and 1.0 mg/l, respectively, compared to hormone-free nutrient medium.

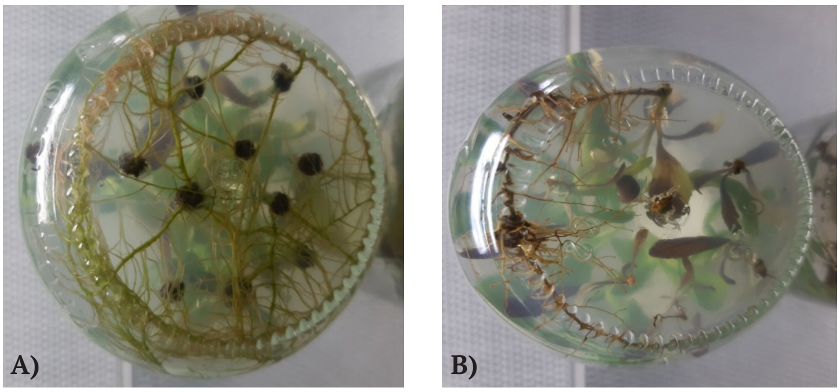

Figure 2. The root system of black poplar hybrids ‘*San Giorgio*’ (A) and ‘*Ghoy*’ (B) on hormone-free nutrient medium ½ MS

Cultivation of regenerating plants on hormone-free nutrient medium ½ MS for two weeks improved the habit of the plants: the stem of the rooted microshoots gradually extended, the leaf plate grew, and the petioles of the leaves lengthened (Fig. 3).

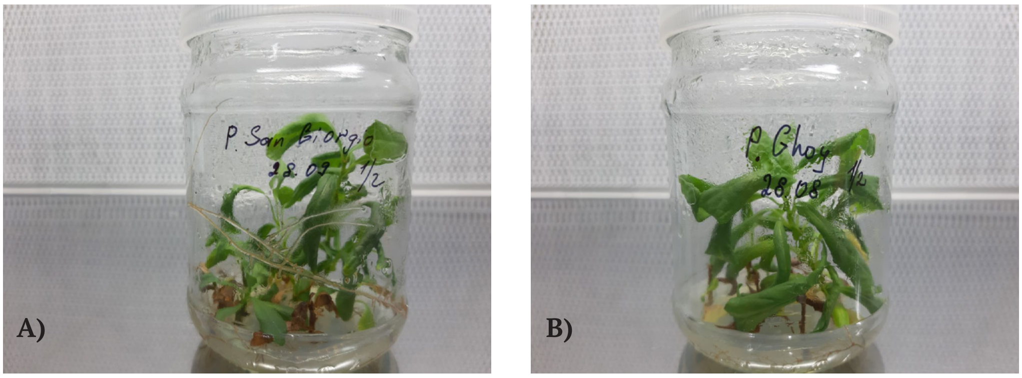

Figure 3. Regenerating plants of *Populus nigra* hybrids '*San Giorgio*' (A) and '*Ghoy*' (B) on a hormone-free nutrient medium ½ MS

During the adaptation of regenerating plants of poplar hybrids, most researchers used multicomponent substrates, which included peat, sand, perlite, vermiculite, soil, which is conditioned upon the ratio of poplars to the soil environment [16; 17].

When the regenerating plants reached a height of 4-5 cm, they were adapted to the conditions of closed soil. Adaptation was carried out on a substrate that included components of peat:sand:perlite in a ratio of 1:1:1. After 4 weeks of adaptation, the survival rate of regenerative plants was over 91%.

Conclusions

An effective method of sterilisation of initial explants of poplar hybrids '*San Giorgio*' and '*Ghoy*' was developed. The highest percentage of aseptic, viable explants was obtained using a 0.05% solution of sodium merthiolate with exposure for 10 minutes. It was found that intense shoot formation occurred with the addition of BAP and kinetin cytokines to the nutrient medium. Low concentrations of IAA and IBA showed a weak stimulating effect on the formation of microshoots of poplar hybrids. The most intense shoot formation occurred on nutrient medium ½ MS + 0.25 mg/l BAP.

Addition of 0.1-1.0 mg/l IBA to the nutrient medium slightly increased the rooting percentage of microshoots. Based on the results of the study, the technology of microclonal propagation of black poplar hybrids '*San Giorgio*' and '*Ghoy*' was developed, which includes obtaining aseptic and viable explants using a 0.05% sodium merthiolate solution with exposure for 10 min, micropropagation on nutrient medium ½ MS + 0.25 mg/l BAP rooting of microshoots on a hormone-free nutrient medium ½ MS, adaptation of regenerating plants to closed soil conditions on a substrate of peat:sand:perlite in a 1:1:1 ratio. The developed technology for obtaining regenerant plants can be used in the future for other black poplar hybrids.

[8] Rapid and efficient regeneration of *Populus*

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Біотехнологічні аспекти розмноження гібридів тополі чорної «San Giorgio» та «Ghoy»

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Анотація. Енергетичну незалежність країни можна вирішити декількома шляхами. Одним із них є створення енергетичних плантацій деревних рослин. Збільшення площі таких плантацій обмежується недостатньою кількістю якісного садивного матеріалу. Значний інтерес при створенні плантацій становлять рослини гібридів роду *Populus*. Враховуючи, що не всі гібриди успішно розмножуються традиційними вегетативними способами, використання біотехнологічних методів, зокрема мікроклонального розмноження, вирішує згадану проблему. Даний спосіб дає змогу отримати велику кількість якісного однорідного садивного матеріалу. Метою досліджень була розробка технології мікроклонального розмноження гібридів тополі чорної *'San Giorgio'* та '*Ghoy*'. При проведенні досліджень використовували загальноприйняті біотехнологічні методи в авторській модифікації на всіх етапах одержання садивного матеріалу рослин-регенерантів гібридів тополі. Дослідженнями встановлено позитивний вплив при отриманні асептичної культури стерилізуючих речовин 0,1 % $AgNO_3$, 2,5 та 1,25 % NaClO, 0,05 % мертіоляту натрію та 0,1 % $HgCl_2$. Найбільшу кількість асептичних життєздатних експлантів отримували культури за застосування 0,05 %-го розчину мертіоляту натрію при експозиції 5 та 10 хв. При укорінені мікропагонів на безгормональному живильному середовищі ½ MS та з додаванням 0,1-1,0 мг/л ІМК встановлено, що кращі параметри укорінення мікропагонів на безгормональному живильному середовищі ½ MS. Адаптацію упродовж 4 тижнів здійснювали в теплиці на субстраті до складу якого входили компоненти торф: пісок: перліт у співвідношенні 1:1:1. Приживлюваність рослин-регенерантів гібридів тополі чорної '*San Giorgio*' та '*Ghoy*' становила більше 91 %. Проведені дослідження та отримані результати будуть корисними для виробників садивного матеріалу та наукового середовища, які працюють у напрямі розвитку відновлювальних джерел енергії через створення енергетичних плантацій швидкорослих деревних рослин

Ключові слова: експлант, живильне середовище, фітогормони, субстрат, садивний матеріал, *in vitro*

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Population Indicators of Sawflies and Concomitant Species of Needle-Eating Species in the Stands of the Prytiasmyn Ridge

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Abstract. Due to the consequences of climate change, namely a decrease in the groundwater level, there is a massive weakening of Scots pine stands in the forests of Ukraine. Against the background of dynamic weakening of trees, annual warm winters, the establishment of warm, sunny, and dry weather in spring contribute to the spread of needle-eating pests, especially sawflies. The purpose of this study was to clarify the species composition and biological features of certain species of needle-eating insects of the Prytiasmyn Ridge and the degree of threat to plantings from needle-eating insects, namely from sawflies and related species. At the stage of reconnaissance survey of pine stands, the method of qualitative and quantitative assessment of sawflies and related species of needle-eating insects was tested. During the survey of plantings of the Prytiasmyn Ridge, Defoliating insects of the following species were found: *Acantholyda erythrocephala*, *Acantholyda posticalis*, *Dendrolimus pini*, *Panolis flammea*, *Sphinx pinastri* isolated, most pine stands predominate in number *Diprion pini* and its concomitant species *Gilpinia frutetorum* and *Gilpinia virens*. The provides results of observations on the population of *Diprion pini* and concomitant species *Gilpinia frutetorum* and *Gilpinia virens* in pine stands with determination of distribution, phenological and biological features. As a result of the survey of stands inhabited by needle-eating insects, it was established in which phase of the outbreak the pest population is, to which categories the breeding centres and biological features of *Diprion pini* and related species under these conditions belong. The population indicators of the common pine sawfly *Diprion pini* and concomitant species in the stands of the Prytiasmyn ridge of the Cherkasy Oblast were evaluated. It was found that the number of these species is increasing, e.g., in 2021 the average number of viable cocoons of *Diprion pini* females was 21%, and the density of cocoons in the detritus (or forest floor) was 0.53 units·m^{-2} compared to the indicators of 2020 of 12% and 0.19 units·m^{-2}, respectively. Similarly, the number of concomitant species *Gilpinia frutetorum* and *Gilpinia virens* is increasing, the average density of cocoons in the detritus (or forest floor) of which was 1.39 units·m^{-2} in 2020, and 1.87 units·m^{-2} in 2021. As a result of the reconnaissance and detailed surveys, foci of the needle-eating insect complex were found with a total area of 128.0 ha, the determined defoliation rate of the crown was from 30% to 50%. The obtained accounting data allow assessing the potential for the reproduction of populations of Defoliating insects and indicate the need for further monitoring observations in the pine stands of the Prytiasmyn ridge

Keywords: phytophagous insects, viable cocoons, defoliation, *Diprion pini*, *Gilpinia frutetorum*, *Gilpinia virens*

Introduction

Recently, starting from 2000, global climate changes have been observed, under which organisms of all trophic levels (plants, phytophages, entomophages) have experienced a violation of the synchronicity of their development, survival, harmfulness, fertility, and range boundaries have changed [1]. On the territory of Ukraine, mass reproduction and cyclical increases in numbers are inherent in insects, mainly from *Lepidoptera* and *Hymenoptera* orders [2; 3]. The most common phytophagous insects of conifers are the pine tree lappet *Dendrolimus pini* L., the red pine sawfly *Neodiprion sertifer* Geoff., and common pine sawfly *Diprion pini* L. [4-6]. The average annual area of centres of mass

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reproduction of pine sawflies in Ukraine exceeds 14 thousand ha and is almost a third of the area of all centres of needle-eating insects [4]. Needle-eating insects cause considerable damage to pine stands, significantly reducing their productivity and protective functions.

The focus of mass reproduction is the area of the plantation, where damage to the crowns of more than 30% and a considerable density of populations of harmful insects is predicted. Mass reproduction of needle-eating insects under favourable conditions is most often observed in well-lit and well-warmed areas of plantations [3; 7]. However, even in favourable years for the common pine sawfly (with a lower temperature threshold of 10.8°C and a sum of effective temperatures of 116.5°C) [4], centres of its mass reproduction do not occur everywhere, but in the most attractive stands, which are determined by the type of forest vegetation conditions, the composition of the tree stand, the age, and completeness of the plantations. Notably, the areas of the cells of defoliating insects can significantly increase due to "cortical drying" [1].

The area of centres of mass reproduction of sawflies and derived (associated) species is determined by the structure of the forest fund, and therefore, Prytiasmyn forests are artificially created by plantations of Scots pine on moisture-deficient, non-grassy sands. The pine forests of Cherkasy Oblast are the object of both global, climate change-related, and local scientific research devoted to the study of the ecological state of the region's forest biogeocoenoses, the characteristics of the grass cover, the dynamics of productive moisture reserves during the growing season, and the development of phytophagous insect populations [6].

Pine sawflies (*Hymenoptera, Symphyta, Diprionidae*) are the most common insects of pine forests in Europe, in particular in Austria, Finland, Estonia, Germany, the Czech Republic [4], especially the monovoltine pine sawfly *Neodiprion sertifer* Geoff. and the common pine sawfly *Diprion pini* L., which develops in one or two generations per year depending on the temperature conditions, namely: the average monthly temperature in May within 15°C and July 18-25°C [2; 4; 8]. Defoliant insects are one of the dominant factors affecting tree growth in temperate and boreal forests, but the impact of climate change on the periodicity and frequency of outbreaks of mass reproduction of these insects is still understudied [1; 4; 7]. V.L. Meshkova et al. [4] performed a graphic analysis of the dynamics of *Diprion pini* L. foci based on individual levels of threat, and it was found that the interval between outbreaks was reduced to three to six years, when the interval between maxima was from 4 to 11 years and an average of 9 years, respectively [2; 7; 9]. Research has established that trees damaged by pine sawflies dry out by 80% or more without the involvement of trunk pests and, due to the fall of the most weakened trees damaged by pine sawflies, the growth of the rest of the trees accelerates [1; 3; 10].

The presence of natural enemies can slightly adjust the number of sawflies and associated species; these include parasitoids (families *Chalcidoidea, Ichneumonidae, Tachinidae*) and predators (birds, small mammals, insects of the families *Elateridae* and *Carabidae*) [10; 11]. According to studies, the influence of a complex of natural enemies on the death of *Diprion pini* L. cocoons is stable, but by the end of the study period (the end of the growing season), the intensity of defoliation slowly decreases, the annual mortality of cocoons from natural enemies ranges from 66% to 80% due to damage by Ichneumonidae and small mammals [10; 11]. Therefore, the combination of best stand characteristics, abiotic factors of the environment and regulation by natural enemies can lead to population fluctuations, and therefore, detailed information on abiotic and biotic regulatory factors is necessary, as well as monitoring of coniferous sawflies and associated species considering changes in climatic conditions.

The purpose of this study was to establish the species affiliation of the "companion" species of sawflies, to identify the specific features of their biology, seasonal development and the degree of threat to plantations according to the corresponding population indicators.

Materials and Methods

Reconnaissance survey of pine plantations of the Prytiasmyn ridge is performed every year on the entire area of forest massifs, these works include an examination of pathogen contamination of natural and artificial forest plantations, as well as on-site inspection of leaves for the warning signs indicating the occurrence of pathogens and phytophagous insects. Surveys are conducted annually, usually in autumn, and they form the basis for drawing up a plan of forest protection measures and sanitary felling for the next year [12; 13]. A detailed (stationary) survey was carried out in 2020 and 2021 in the stands of the Prytiasmyn ridge, which stretches along a strip about 50 km long and 1.5-2.5 km wide along the left bank of the Tiasmyn River, where there are best forest ecological conditions for the reproduction of sawflies (or associated species) and in cells. Table 1 presents the terms of conducting records of needle-eating insects [4; 12].

Table 1. Accounting stages and units of measurement

Species		Accounting stages, accounting time, units of measurement
Needle-eating insects	*Dendrolimus pini*	caterpillar (wintering stage), November, 1 m^2 of litter; caterpillar, April, quantity on 1 tree
	Diprion pini	cocoon (eonymph, pronymph), October, March 1 m^2 of litter
	Neodiprion sertifer	cocoon (eonymph, pronymph), October, March 1 m^2 of litter

When surveying centres of mass reproduction of pine sawflies, a spring count of cocoons in the litter was carried out, setting up test areas in plantations with different degrees of crown eating, counts were carried out on samples (sites or accounting trees). The total number of samples in the cell was at least 20, in forest areas with homogeneous plantations, samples were placed evenly along the planned routes, in quarters with heterogeneous plantations, samples were placed in large sections. To record the insects in the litter, samples of 1 m^2 (2×0.5 m) were laid under the trees with the smaller side adjacent to the tree, and the larger side along the radius of the crown projection, the top layer of the litter was discarded, then carefully examined, removing the rest of the litter in layers, and then soil to a depth of 5-8 cm. All insects (at different stages of development), individually alive, affected by diseases and damaged by parasites or predators were selected and counted [12; 13].

When recording, it is important to be able to distinguish healthy pupae (cocoons) from those affected by parasites and pathogens. A healthy pupa makes vigorous abdominal movements when squeezed from the sides. When leaving the imago pupa, they open diagonally with large lids from the head to the middle of the front side of the abdomen. When the parasites leave the pupae, they leave round holes of diverse sizes in the walls. Pupae with signs of damage by bacterial pathogens contain a brown liquid with a sharp unpleasant smell, with signs of mycosis damage – hard and covered with fungal mycelium [4; 12; 13]. The cocoons of sawflies are opened with a round lid on the entire width of the cocoon from the end when they fly out, the parasitised cocoons when they fly are left in the walls, as well as in the end, the holes are always smaller. When damaged by entomophages and predators (rodents), holes of irregular shape are formed on cocoons and pupae [12; 13].

The species composition of overwintering pests was determined, isolating the cocoons of the common pine sawfly and related species. When examining the cocoons of the common pine sawfly, the following were selected: whole cocoons without any holes; damaged by entomophages (wireworms, turuns, etc.), which have one or more holes of irregular shape and different sizes on the surface, and are empty inside or with larva remains; damaged by mouse-like rodents, which have an elongated hole of arbitrary shape, depressed on the sides, and empty inside; the cocoons hatched by the birds have a membrane bent to the sides in the form of a triangular patch at the place of damage; parasitised cocoons have regular round holes, but unlike the cocoons from which adult sawflies emerged, they are much smaller.

Whole cocoons were analysed to identify the sex index (the ratio of females to males). For this, whole cocoons were divided by size, larger cocoons measuring 9-10 mm were assigned to females, and smaller ones (7-8 mm) – to males, the number of females was divided by the number of males, while finding the ratio between females and males in the wintering population of sawflies (♀:♂).

The average density of cocoons (*p*) at the size of the accounting plot of 1 m^2 (2×0.5 m) was calculated according to the following formula:

$$\rho = \frac{n\ (\text{cocoons})}{n\ (\text{accounting areas})} \qquad (1)$$

The threat of 100% eating of plantations by *Diprion pini* L. larvae in terms of the number of viable ones per 1 m^2 is 13 female cocoons per 1 m^2.

Externally intact female and male cocoons were analysed for diapause, parasite infestation, and disease damage by dissecting the cocoons and carefully examining hibernating individuals with binoculars and a magnifying glass, a total of 471 cocoons were analysed in 2020 and 726 cocoons in 2021. When infected with fungal diseases inside the cocoon, the larva is mummified and hard, the tissue is filled with white, red, green, pink, mycelium. If affected by bacterial diseases, the hibernating larvae in the cocoon have an unpleasant smell, are black, filled with a black or red liquid. Viral diseases are diagnosed through microscopic analysis, visually – in the cocoon, the larva is liquefied and transformed into a cloudy, odourless liquid.

Spring surveys were performed by surrounding model trees and collecting larvae of sawflies and associated species on a total area of 128 ha. The larvae feeding in the crown were collected by rounding and the state of defoliation was determined approximately. The collected larvae were subsequently divided by species and age, age was determined by the width of the head capsule (Table 2) [12].

Table 2. The width of the head capsule of larvae of different ages, mm

Age	I	II	III	IV	V	VI
Head capsule width, mm	0.5	0.8	1.1	1.4	1.8	2.2

The question of determining the age of larvae in the study of population indicators is important because without an accurate determination of age it is difficult to signal the timing of the development of defoliant insects and to prescribe appropriate control measures.

Results and Discussion

During the survey of experimental plantations, a complex of defoliant insects was discovered, which included 8 species from 6 genera and 5 families (Table 3). During the inspection of the forest, the following species were found: the red-headed *Acantholyda erythrocephala* and the pine star *Acantholyda posticalis* saw-weavers, the pine silkworm *Dendrolimus pini*, the pine weevil *Panolis flammea*, the pine weevil *Sphinx pinastri*, the common pine sawyer *Diprion pini* and its derived species – shrub gilpinia *Gilpinia frutetorum* and greenish gilpinia *Gilpinia virens* with different frequency of occurrence. Larvae of sawflies damage pine plantations of various ages, including undergrowth and open forest crops, which, in case of a rapid increase in numbers, leads to substantial loss of needles, deterioration of the sanitary condition of plantations, loss of growth and death of individual trees. Apart from common (*Diprion pini* L.) and red (*Neodiprion sertifer* Geoffr.) pine sawflies, there are so-called “combined” species in pine forests that damage needles at the same time as these species [9].

Table 3. Distribution of needle-eating insects in the plantations under study

Family	Genus	Species	Frequency of occurrence
Pamphiliidae	*Acantholyda*	*Acantholyda erythrocephala*	Isolated
		Acantholyda posticalis	Isolated
Lasiocampidae	*Dendrolimus*	*Dendrolimus pini*	Isolated
Noctuidae	*Panolis*	*Panolis flammea*	Isolated
Sphingidae	*Sphinx*	*Sphinx pinastri*	Isolated
Diprionidae	*Diprion*	*Diprion pini*	Crowded
	Gilpinia	*Gilpinia frutetorum*	Crowded
		Gilpinia virens	Crowded

Notably, the species complex of defoliant insects in this region is typical for stands dominated by Scots pine [1; 3; 7], associated species of sawflies, namely *Gilpinia frutetorum* and *Gilpinia virens*, form stable centres in favourable years [9]. The obtained data are consistent with studies of needle-eating insects on the territory of Ukraine, namely in Zhytomyr [1; 3] and Luhansk Oblast [7], Kyiv and Chernihiv Polissia and Forest Steppe [6], but the listed species occur unevenly across the entire area of plantations. As the data in the Table 4 suggests, the dominant species are the larvae of *Diprion pini*, *Gilpinia frutetorum* and *Gilpinia virens*, the caterpillars of *Sphinx pinastri* and *Dendrolimus pini* were found singly.

When surveying the nests of the common pine sawfly, a considerable increase in the number of "accompanying" species of pine sawflies was noted in different regions [3; 7; 9]. In connection with the lack of data on the biological characteristics, distribution and development of these species, it is difficult to appoint and promptly perform forest protection measures.

Table 4. The survey results obtained from the model trees

Location		Area, ha	Seq. No.	Species		
Quarter	Section			*Sphinx pinastri*	*Dendrolimus pini*	*Diprion pini* and derived types
22	1	14.7	1	0	1	51
21	2	7.2	1	0	0	47
20	4	16.7	1	0	1	43
			2	0	0	39
20	5	7.4	1	0	1	94
18	3	1	1	0	0	103
10	11	6	1	0	0	0
9	8	10.8	1	0	0	46
9	7	9.0	1	0	0	3
8	5	37.3	1	0	0	26
			2	0	0	17
8	13	3.8	1	2	1	151
7	5	14.1	1	0	1	23
Total		128.0		2	6	643

A total of 643 larvae of sawflies were collected, the main part of which was larvae of the shrub gilpinia, about 75%, and the rest – 25% of the larvae of the greenish gilpinia. *Gilpinia* cocoons and larvae were ubiquitous in the stands under study. In contrast to the common pine sawfly, larvae of shrub gilpinia live alone and are a typical "companion" species in sawfly populations [14-16].

According to the timing of feeding, needle-eating sawflies are divided into two groups. Larvae of the Group I species feed in the spring and cause damage at the same time as the red pine sawfly (from the end of April to mid-June) [9; 16], did not occur in the plantations under study. Larvae of the Group II species feed simultaneously with the common pine sawfly (spring generation in June, autumn generation in August-September), namely *Gilpinia frutetorum*, and *G. virens* [16]. Unlike needle-eating sawflies, larvae of *Gilpinia frutetorum* and *Gilpinia virens* are solitary, and are a typical "companion" species in sawfly populations. Larvae of greenish gilpinia occur singly everywhere and never reproduce en masse [9].

An analysis of the age structure of *Gilpinia frutetorum* and *Gilpinia virens* larvae was carried out (Table 5), as a result of which the predominance of II-III age class larvae was established. Notably, in the stands under study, larvae, and cocoons of *Diprion pini* and associated species were found ubiquitously (Table 6).

Table 5. Analysis of the age structure of the larvae of greenish and shrub gilpinia

Phytophage insect	I		2		III		IV		V	
	pcs.	%	pcs.	%	pcs.	%	pcs.	%	pcs.	%
Gilpinia virens	26	16	90	56	45	28	0	0	0	0
Gilpinia frutetorum	92	19	202	42	159	33	29	6	0	0

Table 6. Average population indicators of common *Diprion pini*

Number of embedded samples	Viable cocoons		Damage caused by entomophages, pcs./%	Affected by mycoses, pcs./%	Dead, pcs./%
	Females, pcs./%	Males, pcs./%			
2020					
150	7/12	5/9	27/45	18/31	2/3
2021					
150	20/21	14/15	27/30	23/25	8/9

The analysis of collected cocoons with a distribution by viability and sex, considering the number of affected, damaged and dead, allowed establishing that the number of cocoons of the common pine sawfly and related species increased in 2021, compared to 2020, due to a sharp increase in the proportion of females in the population (Fig. 1).

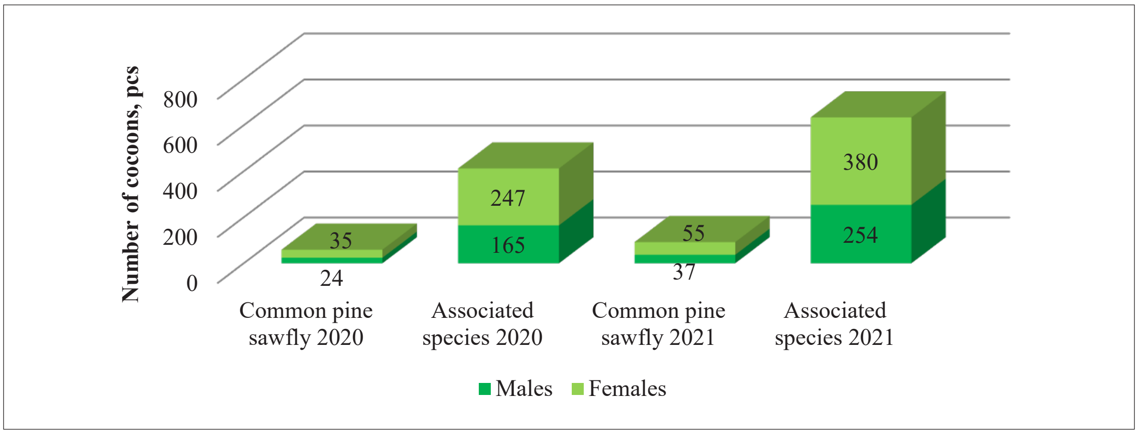

Figure 1. Distribution of cocoons of pine sawflies and related species by sex, pcs.

Among the *Diprion pini* cocoons collected in 2020-2021, no more than 20% of the cocoons were intact. Among the 59 intact cocoons examined in 2020 (by external signs), only 12 were found to be viable, i.e., contained living aeonymphs, when in 2021, 34 viable cocoons were found among 92 cocoons. Analysing the obtained data, the average number of viable cocoons of common pine sawfly females was 12% in 2020, and 21% in 2021, respectively, so this indicates favourable conditions for the development of the population and the potential for increasing the number in the future. The average density of cocoons in the test plots in the litter was 0.19 pcs·m^{-2} in 2020, and 0.53 pcs·m^{-2} in 2021. Mostly, the cocoons of the common pine sawfly were damaged by entomophages – 45% and 30%, the share of cocoons affected by mycoses was 31% and 25%, the share of dead cocoons – 3% and 9%, respectively.

During the study, the population indicators of accompanying species were analysed by year: viable cocoons of females of derived species (shrub gilpinia and green gilpinia) in 2020 – 13%, in 2021 – 11%, respectively (Table 7, Fig. 2). From all the test plots that were planted in the plantations in 2021, 634 intact cocoons of related species of the pine sawfly, namely greenish and shrub gilpinia, and 412 cocoons in 2020 were found, of which the proportion of viable ones was 117 and 86 cocoons, respectively.

Table 7. Population indicators of derived species *Gilpinia frutetorum* and *Gilpinia virens*

Number of embedded samples	Viable cocoons		Damage caused by entomophages pcs./%	Affected by mycoses pcs./%	Dead, pcs./%
	Females, pcs./%	Males, pcs./%			
2020					
150	52/13	34/8	193/47	88/21	45/11
2021					
150	70/11	47/7	379/60	126/20	12/2

Figure 2. Collected cocoons of *Diprion pini* and related species

The average density of cocoons in the litter on the trial plots was 1.39 pcs·m^{-2} in 2020, and 1.87 pcs·m^{-2} in 2021.

As can be seen from the above data, the majority of cocoons of the derived species of shrub gilpinia and greenish gilpinia are damaged by entomophages – 47% and 60%, the share of cocoons affected by mycoses is 21% and 20%, the dead are 2% and 11%, respectively, in 2020 and 2021.

During the research, the level of defoliation of the pine plantations was measured (Fig. 3). According to the conducted reconnaissance and detailed surveys, teh study established the presence in the plantations of the Prytiasmyn ridge of centres of the complex of needle-eating insects with a total area of 128.0 ha, the determined average defoliation rate of the crown was from 30% to 50%. Therefore, further study of the biology of the "companion" species of sawflies will allow establishing the regularities of their relationships in complex centres and determining the degree of danger for pine plantations.


Figure 3. Defoliation of the surveyed forest stands

According to the classical scheme of A.I. Ilyinsky (1952), outbreaks of mass reproduction of needle-eating insects form seven generations of phytophagous insects, which develop in four phases [12]. In the first (initial) phase, the population size rapidly increases by 2-4 times (compared to the population size index before the outbreak), in the second phase (population growth), centres of mass reproduction are formed, in the third phase (the outbreak itself) – the number of individuals in the population increases, and in the fourth (crisis phase) – it sharply decreases. According to the results of the conducted forest pathology survey, it was established that the population of *Diprion pini* and related species *Gilpinia frutetorum* and *Gilpinia virens* is on the verge of a tangible threat of damage to the plantations of the Prytiasmyn ridge and the centre is in the second phase of development – the phase of population growth. Therefore, it is currently expedient to carry out exterminating measures to reduce the population and its spread.

Conclusions

In 2020-2021, a complex of defoliant insects was found in the stands of Prytiasmyn pine forests, which includes 8 species from 6 genera and 5 families. The biological features of the species that may have economic value, namely the red-headed *Acantholyda erythrocephala* and the pine-star *Acantholyda posticalis* saw-weavers were specified, the pine silkworm *Dendrolimus pini*, the pine weevil *Panolis flammea*, the pine weevil *Sphinx pinastri*, the common pine sawfly *Diprion pini* and related species – the shrub gilpinia *Gilpinia frutetorum* and the greenish gilpinia *Gilpinia virens*. In the conditions of the Prytiasmyn ridge, all identified species of insects occurred, but sawflies and their associated species dominated. Population densities of all needle-eating insects' species were low, but cocoon densities of both common and associated pine sawfly species increased in 2021 compared to 2020. Among the factors regulating populations of pine sawflies, the leading role was played by entomophages, which damaged the majority of cocoons of related species and sawflies, and mycosis.

Considering the fact that the stands of the Prytiasmyn ridge are considerably weakened, defoliation of needles in the cell is already above average in the vast majority, and the feeding of pests will continue throughout September-October, damage to needles can lead to a sharp increase in the defoliation rate and a considerable weakening and deterioration of the sanitary condition in the pine stands. Further study of the biology of associated species of pine sawflies will reveal patterns of their interaction in complex centres and determine the degree of danger for pine plantations.

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Популяційні показники пильщиків та супутніх видів комах-хвоєгризів насаджень Притясминської гряди

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Анотація. У звя'зку з наслідками кліматичних змін, а саме пониженням рівня ґрунтових вод, у лісових масивах України спостерігається масове ослаблення насаджень сосни звичайної. На фоні динамічного ослаблення дерев, щорічних теплих зим, встановлення теплої, сонячної та сухої погоди навесні сприяють розвитку та поширенню хвоєгризучих шкідників, особливо пильщиків. Метою досліджень було уточнення видового складу та біологічних особливостей окремих видів комах-хвоєлистогризів Притясминської гряди та ступеня загрози насадженням від хвоєгризів, зокрема, від пильщиків та супутніх видів. На етапі рекогносцирувального обстеження соснових насаджень, було здійснено апробацію методики якісної та кількісної оцінки пильщиків та супутніх видів комах-хвоєгризів. Під час обстеження насаджень Притясминської гряди виявлено комах-дефоліантів наступних видів: *Acantholyda erythrocephala*, *Acantholyda posticalis*, *Dendrolimus pini*, *Panolis flammea*, *Sphinx pinastri поодиноко*, в більшості соснових насаджень переважають за чисельністю *Diprion pini* та його супутні види *Gilpinia frutetorum* та *Gilpinia virens*. Наведені результати спостережень за популяцією *Diprion pini* та супутніх видів гільпінії чагарникової *Gilpinia frutetorum* та гільпінії зеленуватої *Gilpinia virens* у соснових насадженнях з визначенням поширення, фенологічних і біологічних особливостей. У результаті обстеження насаджень, заселених хвоєгризучими комахами, встановлювали у якій фазі спалаху перебуває популяція шкідника, до яких категорій належать осередки розмноження та біологічні особливості *Diprion pini* та супутніх видів у даних умовах. Оцінено популяційні показники звичайного соснового пильщика *Diprion pini* та супутніх видів у насадженнях Притясминської гряди Черкаської області. Визначено, що чисельність зазначених видів зростає, так, у 2021 році середня кількість життєздатних коконів самиць *Diprion pini* становить 21 %, а щільність коконів у підстилці – 0,53 шт·м$^{-2}$ за показників 2020 року 12 % та 0,19 шт·м$^{-2}$ відповідно. Аналогічно зростає чисельність супутніх видів *Gilpinia frutetorum* та *Gilpinia virens*, середня щільність коконів у підстилці яких становила у 2020 році 1,39 шт·м$^{-2}$, а у 2021 році – 1,87 шт·м$^{-2}$. За наслідками проведених рекогносцирувальних та детальних обстежень виявлено осередки комплексу комах-хвоєгризів загальною площею 128,0 га, окомірно встановлений показник дефоліації крони становив від 30 % до 50 %. Отримані облікові дані дозволяють оцінити потенційні можливості розмноження популяцій комах-дефоліантів та свідчать про необхідність проведення подальших моніторингових спостережень в соснових насадженнях Притясминської гряди

Ключові слова: комахи-фітофаги, життєздатні кокони, дефоліація, *Diprion pini*, *Gilpinia frutetorum*, *Gilpinia virens*

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Evaluation of Field-Based Burn Indices for Assessing Forest Fire Severity in Luhansk Region, Ukraine

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Abstract. Evaluation of forest fire severity is a basis of post-fire forest management. Remote sensing-based methods enable reliable delineation of fire perimeters, however, assessments of the degree of forest damage need to be verified and adjusted through field sampling. The forest damage assessment conducted in this study is useful for practitioners to understand and justify the design of clear cuts for restoration purposes. Thus, the aim of the study is to verify the different approaches to field assessment of forest fire severity. In this paper, the authors present a site-specific assessment of large wildfires in Luhansk oblast, Ukraine occurred in 2020 using field-based burn severity indices. The Composite Burn Index (CBI) and the Geometrically Structured Composite Burn Index (GeoCBI) were used to estimate the extent of forest damage. The Burned Area Emergency Response (BAER) methodology was also tested to assess the extent of soil damage. The authors used PlanetScope images to delineate perimeters of burned areas. These perimeters were overlaid over a forest inventory database to extract forest attributes and site characteristics for all forested and unforested areas affected by fires. Within the fire perimeters, the burned area was stratified into six strata to independently account for forest damage in diverse types of land cover. In total 73 test plots were proportionally distributed among different classes of land cover to assess fire severity using CBI, GeoCBI, and BAER approaches. It was found that the fire's footprints covered 39,782 hectares. Among that area, 21.2% were forested lands. About 78% of burned forests were pine plantations. The highest fire intensity levels were estimated within pure pine plantations that were grown in very dry sites, while the lowest ones were associated with hardwoods forests in moisture site conditions. The average estimates of fire severity using the field-based indices varied within strata (CBI>GeoCBI) which could be an issue for assessing burn severity using remote sensing-based approaches. The authors also concluded that the BAER methodology contributed less to assessing the fire intensity because soil burn severity is not directly related to vegetation damage. This work creates a foundation for further assessment of fire severity using satellite imagery. As a result of this study, a spatial data set of sample plots was proposed that can facilitate calibrating approaches used to map fire severity in the region

Keywords: field-based burn severity indices, forest damage, burned area, site condition

Introduction

Forest fires are one of the main natural disturbances of Scotch pine forests in the southern and eastern regions of Ukraine. Wide use of fires to burn agriculture residues in Ukraine [1] results in permanent presence of ignition sources in landscapes of the region. During periods of extreme weather danger (e.g., low fuels moisture and high wind speed) with strong wind, agricultural fires can enter pine forests and within hours reach high intensity that pose a direct threat to villages located close to forests, similarly to other fire prone landscapes in the Mediterranean region or western United States [2; 3]. From a forest management perspective, the most obvious consequences of fires are accumulation of large amounts of dead biomass, degradation of forest stands, and reduction in their capacity for carbon sequestration [4; 5].

Problem of forest fires in Ukraine essentially escalated during the last two decades due to climate and land-use changes: single large fire event reached unprecedent

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for the country levels (15-60,000 ha) while occurrence of extreme fires has become more frequent [6; 7]. Since 2015 extreme fires repeatedly occurred every 3-4 years all over the country: the Chornobyl Exclusion Zone (1992, 2015, 2020) [6; 8], Kherson oblast (2007, 2012) [6; 9]; Zhytomyr, Lugansk, Kharkiv oblasts (2020) [10]. The main drivers of all large fires of the last decade were massive agricultural burnings combined with drought, fast wind, and essential fuel load in overcrowded Scotch pine plantations that drove extreme fire behaviour [1].

During second half of XIX century, Ukraine was a relatively safe country with low frequency of extreme forest fires [6; 9; 10]. Thus, the forest fire management in Ukraine lacks a national policy toward shifting to landscape fire management [6; 7]. This could be illustrated with the absence of specific fire research centres that study landscape fires. First fire lab in Ukraine was established in 2013 at the National University of Life and Environmental Sciences of Ukraine supported by the Global Fire Monitoring Centre (GFMC) and Council of Europe [11; 12]. Recently, a few studies were undertaken for postfire damage research mostly based on ground assessment of stands burned [13; 14]. Under these circumstances, many issues related to landscape fires in Ukraine remain unexplored, for example, methods for assessing forest fire damage, remote sensing-based forest fire mapping, etc. Post-fire management in Ukraine regularly faces a challenge because of the lack of empirical evidence on the accuracy of fire severity assessment in various regions and forest types while good restoration practices require detailed information on losses of ecological and social functionality of burned forested landscapes that are related to the extent and severity of fires [14; 15].

Today, remote sensing methods and numerous products developed using satellite imagery enable assessment not only the perimeters of fires but also the degree of forest damage [2; 16]. While a rapid evaluation of the spatial pattern of burned areas can be performed using merely satellite imagery, detailed information on forest damage is highly dependent on field data collected after the fire [17]. In most cases, remote sensing-based indices of fire severity and any estimates of the degree of forest damage need to be verified and adjusted on the site.

Characterising wildfire severity over large geographical regions is challenging due to the necessity of measurements of various parameters (e.g., char height, foliage death etc.) taken in multiple locations of a landscape. Often the accessibility of such location can be limited due to topography factors, logistic constraints, or threats to human life such as in the war zone. Thus, remote sensing approaches provide strong support for decision-making regarding recently burned forest areas [16; 18]. A reliable evaluation of the fire effect imposed on the forest ecosystem though is needed to produce the most accurate maps of burned areas.

Several methods have been proposed to estimate burn severity from field sampling using an examination of post-fire soil and vegetation conditions [2; 19; 20]. Among them, the Burned Area Emergency Response (BAER) process was developed for the rapid assessment of wildfires on soils [21; 22]. Safford et all. [22] criticised the underlying methodology and stated that BAER maps cannot be used to estimate fire effects on vegetation. Therefore, figuring out how tree mortality is changing in response to fire severity is a key concern of many studies. For example, Whittier and Gray [23] developed a fire severity classification scheme based on tree mortality regarding species and tree sizes in the western USA.

Composite Burn Index (CBI) is well documented and widely used by forest community to support an operational methodology for burn severity assessment [17], specifically at national scale in the USA under the framework of the FIREMON (Fire Effects Monitoring and Inventory Protocol) project [24]. The CBI index considers five vertical strata of vegetation that are inspected during field visits. Based on the effect of fire on vegetation, numerical scores are assigned to each stratum (from 0 – unburned to 3 – completely burned) and averaged into understory, overstorey, and overall composite burn rating. Stambaugh et al. [25] demonstrated that the CBI could be successfully applied to produce more accurate fire severity maps within forested areas than within grasslands. Further evaluation of the CBI in conjunction with remote sensing data showed a very diverse variation between field-based and remote sensing-derived fire severity indices [26]. The issues in retrieving CBI and comparing its performance with different indices to evaluate forest fire severity is widely discussed in many publications [27-29]. An updated version of the CBI namely GeoCBI (Geometrically structured Composite Burn Index) was proposed [2] to improve the retrieval of burn severity from remote sensing data. In contrast to the CBI, this version of the burn index considers the fraction of the vegetation (FCOV) that has a positive effect if remote sensing data are utilised for mapping fires [16].

Given the remarkable progress in developing methods for fire severity assessment both using field- and remote sensing-based approaches, there was no detailed examination of such approaches in Ukraine. Since the occurrence of large wildfires has increased in different regions, knowing the impact of fire on forest cover is of foremost importance for fire management [12]. To the authors' best knowledge, there were only a few studies focused on fire severity assessment in Ukraine [8; 13; 14], however, none of them relied on field-validated data to support mapping efforts.

This paper presents a site-specific assessment of large wildfires in Luhansk oblast, Ukraine occurred in 2020 using field-based burn severity indices. The specific objective of this study was to test performance of the CBI and GeoCBI for fire severity assessment in various land cover and forest types. In Ukraine, methods for estimating the intensity of forest fire severity have not yet been studied. This work is the first attempt in Ukraine to examine various field-based fire severity indices that can support accurate forest fire mapping in the region.

Materials and Methods

Study area

This study was conducted in the Luhansk region, which is the easternmost in Ukraine. Luhansk region is characterised by three types of landscapes – agricultural, steppe and forest. Forests cover 8.6% of the region's territory and are very unevenly distributed, 87% of the territory is occupied by agricultural lands and natural steppes. The forests are mostly located in the basins of the Siversky Donets and Aidar rivers (Kreminsky and Stanychno-Lugansky districts). The total area of forests in the region is 339.6 thousand hectares more than 250 thousand hectares of which are occupied by planted forests [30].

The climate of Luhansk oblast is fire prone and characterised by hot, windy, and dry summers often with drought-dry phenomena, cold and snowless winters. The average annual air temperature varies between +7.5°C and +8.5°C. The average temperature in July is +21°C. Precipitation in the oblast is unevenly distributed, most of it falls in the southwestern part of the region, and the least in the central, eastern, and north-eastern parts. The average rainfall per year is 400-500 mm [31] but recent studies indicate the essential changes in climatic characteristics in the nearest future [32].

The study area is in the western part of Luhansk oblast and fits into a rectangle 100×50 km (Fig. 1). The region where the fires occurred is sandy arenas along the Siverskyi Donets river, where pure pine plantations have been created in 1950-1960. Typical feature of this region is the mosaic of the landscape's types – pine forests alternate with forestless steppes with deciduous islands in the depressions.

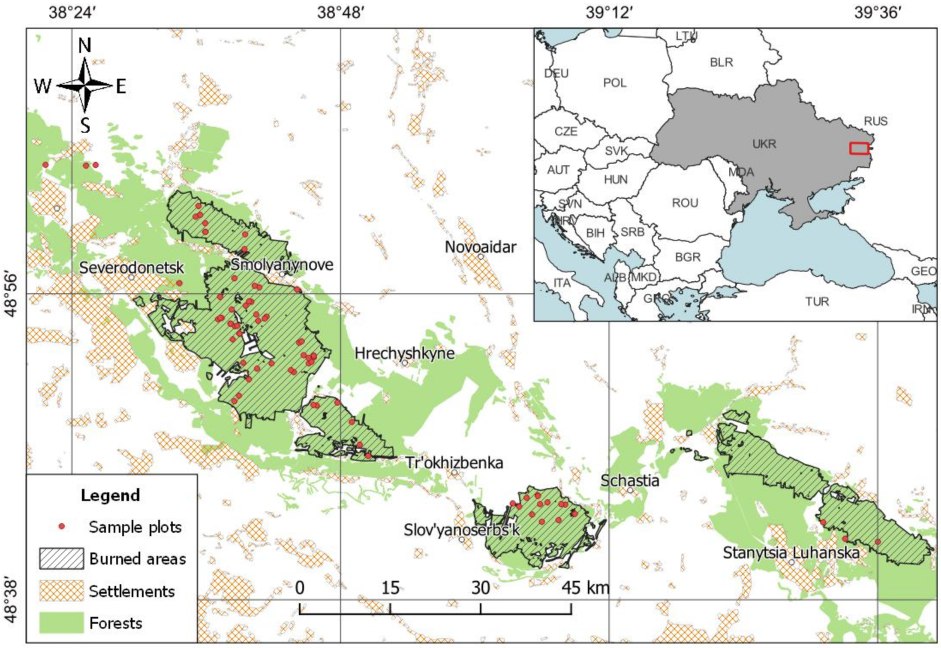

Figure 1. Study area overlaid with perimeters of burned areas and distribution of sample plots

Two large forest fires occurred in the Luhansk oblast in 2020. The first forest fire with a total area of 24,6 thousand hectares occurred in July 2020 in Severodonetsk and Novoaydar districts, which destroyed 84 houses, damaged 24 houses in Smolianynove village, killed 5 people died, and 471 were injured. The second series of fires happened in the same districts in September–October 2020 on a total area of 15,2 thousand hectares. As a result, 32 settlements were damaged, 573 houses were burned completely and 60 houses were damaged by fires, 12 people died, and 390 were injured [10]. The fires of 2020 became the largest and the most catastrophic in the history of this region.

Remote sensing data

The authors of this paper used data on thermal anomalies which were interactively analysed using web-interface [33] to detect fire events in the region. Thus, the dates of two large fires were identified, which occurred between July and October 2020.

PlanetScope multispectral satellite images PlanetTeam [34] were used to determine approximate perimeters of burned areas. The images were chosen according to the start (July 6, 2020) and the end (October 9, 2020) dates of the fire period that was identified using MODIS [35] and VIIRS [36] data on thermal anomalies. PlanetScope satellite images, acquired during July 3-5, 2020, characterised the state of the territory before the fire, while those acquired on October 9, 2020, depicted the state of the territory after the fire. Considering that the analysis was done visually, there were no specific requirements for the image mosaics regarding seasonality of images acquisition (e.g., summer or autumn images), but the dates were chosen based on availability of cloudless images. High spatial resolution (3 m) together with spectral bands combination (Red-NIR-Green) allowed us to outline perimeters of burned areas that consisted of nine separate polygons (Fig. 1).

Forest inventory data

The forest inventory database provided by the Ukrainian State Forest Project Association (PA "Ukrderzhlisproekt") was incorporated in the study to characterise land cover and attributes of forest stands affected by fires in 2020. This information was coupled with polygon coverage and used to design field sampling. For each forest polygon, the authors of this paper identified its area, a land cover type (i.e., stocked forest, and temporally unforested area, non-forest land), and attributes of forest stands (dominant species and site condition). They are characterised by the following indicators: the total area of forested land is 172 thousand hectares; 18% of forests are forests of natural origin; the predominant tree species is Pinus sylvestris L. (78% of the area), the rest of the area is occupied by such tree species as *Quercus robur* L., *Betula pendula* Roth. *Alnus glutinosa* (L.) Gaerth., *Populus nigra* L. Forest land distribution by site conditions according to the Ukrainian forest types classification [36] shows that most areas are characterised by poor and dry types – 82% (A_1, A_2, B_1, B_2; where A, B, C, D – soil fertility (from poor to fertile), and 0, 1, 2, 3, 4, 5 – soil moisture (from very dry to very wet)), the remaining conditions occupy insignificant areas less than 4%.

Field data

Field sampling

A stratified random sampling was applied to allocate sample plots for burn severity assessment within perimeters of burned areas. The authors used information extracted from the database of PA "Ukrderzhlisproekt" on land categories, types of forest conditions, and dominant tree species before the fire to stratify the burned areas into six homogeneous strata (Table 1). The authors' stratification approach aimed to sample diverse types of land cover (forested and temporally unforested areas, non-forest lands), and potentially characterise the different effects of fire on vegetation. To address the combined effect of species composition and site conditions on fire behaviour, the pine-dominated forests that grow in site conditions A_{2-3} and B_{2-3} were distinguished [37], which are optimal for Scots pine. All dry sites were also disaggregated regardless of their soil fertility and species composition (A_{0-1}; B_1; C_1; D_1). The remaining forested areas represented relatively wet site conditions with various soil fertility. In the authors' stratification, two separate strata were also created for temporally unforested areas in dry site conditions as well as other unforested and non-forest lands. The minimum number of test plots in the stratum accounted three samples, while their maximum number reached up to 25 samples. The number of sample plots in each stratum was established proportionally to the area of the stratum but finally was slightly changed in the field due to proximity to the zone of the military conflict and the inaccessibility of certain plots. As many as 73 sample plots were established within the study area that were accompanied by five control plots located on unburned areas (Fig. 1). The sampling frame for field survey was created in Quantum GIS (3.2.1), the location of each plot was identified on the site using GPS.

Table 1. The scheme of stratification of the study area

Code of the strata	Land cover class before fire	Site conditions*	Dominant species	Percentage of the area, %	Number of plots
1	Forested areas	A_{2-3}	Scots pine	27	25
2	Forested areas	B_{2-3}	Scots pine	22	13
3	Forested areas	A_{0-1}; B_1; C_1; D_1	Deciduous species, Scots pine	10	17
4	Forested areas	A_{2-3}; B_{2-3}; B_4; C_{2-5}; D_{2-5}	Deciduous species	14	4
		C_{2-3}; D_{2-3}	Scots pine		
5	Temporally unforested areas	A_{0-1}; B_1; C_1; D_1	–	9	6
6	Other temporally unforested areas and non-forest lands	A_{2-3}; B_{2-3}; B_4; B_{2-5}; D_{2-5}	–	18	3

Note: * A, B, C, D – soil fertility (from poor to fertile) and 0, 1, 2, 3, 4, 5 – soil moisture (from very dry to very wet)
Source: [37]

The implemented scheme is justified by the similarity of site conditions (soil fertility and moisture) which determine the similarity of forestry measures.

Field-based burn indices

To assess field-based burn severity, each sample plot was visually evaluated using the CBI index [17; 24], and its geometrically modified version, namely the GeoCBI index [2]. These indices provide a comprehensive scoring of the degree of fire damage imposed to various strata of vegetation, i.e., duff, litter, shrubs, stands.

According to the field protocol, the average post-fire conditions are visually assessed on sample sites within a radius of 15 m by five separate layers: (A) substrates; (B) herbs, low shrubs, and trees less than 1 meter, (C) tall shrubs and trees 1 to 5 meters; (D) intermediate trees (subcanopy, pole-sized trees); (E) big trees (upper canopy, dominant, codominant trees). The CBI considers litter and fuel consumption, soil colour change, leaf or cover change, canopy mortality and soot height. These attributes are evaluated in numerical scores from zero (unburned) to three (completely burned). The scores for each group are averaged over the total area. Different attributes for each layer are evaluated and averaged in the protocol [24]. The GeoCBI index additionally considers the percentage of projected coverage of each stratum (FCOV) and is therefore more efficient in terms of estimating the intensity of fires [2; 16]. The fraction of coverage (FCOV) of the vegetation, with respect to the total plot was visually evaluated for separate layers B, C, D and E. FCOV was scored from 0 to 100 percent and used as a weighting factor. The GeoCBI was calculated as follows:

$$\text{GeoCBI} = \frac{\sum_{m_1}^{m_n}(CBI_m \cdot FCOV_m)}{\sum_{m_1}^{m_n} FCOV_m} \tag{1}$$

where *m* refers to each vegetation layers (B, C, D, and E), and *n* denotes the number of the strata.

Furthermore, soil samples were taken from each test plot to determine the degree of fire impact on its structural characteristics according to the BAER approach [21; 22]. On each plot, soil properties were evaluated (ground cover, ash colour and depth, soil structure, condition of roots, and water repellence) using special form as it is described by Parsons et al [21].

Finally, a series of images were taken on each sample plot using technique of creating 360-degrees panoramic photography of virtual reality VR360 [38; 39].

Results and Discussion

Fire extent

Using PlanetScope multispectral satellite images, the perimeters of the burned areas were determined and the approximate area affected by fires was estimated to be 39.782 hectares (Fig. 1). The outlines of the fires and the forest inventory data allowed us to evaluate the scale of forest losses in the region.

The characteristics of the damaged landscapes were evaluated based on the established areas affected by fires, using the forest inventory database (Table 2 and Table 3). Among the damaged forests, 78% of the area is pine, 6% birch, and other tree species occupying less than 5% of forested area.

Table 2. Distribution of the burned area by site conditions

Forest site index	Area, thousand, ha	Proportion
C_4	0.452	0.011
C_3	0.579	0.015
C_2	0.871	0.022
B_3	1.818	0.046
B_1	1.899	0.048
A_1	4.165	0.105
A_2	13.26	0.333
B_2	13.625	0.342
Others	3.112	0.078
Total	39.78	1.00

Table 3. Distribution of the burned area by the land covers

Land cover type	Area, thousands ha	Proportion
Forested lands (i.e., planted and natural forests)	8.436	0.212
Unforested (i.e., harvested areas, glades, unstocked forests, forest plantation less than 8-year-old, dead forests, etc.)	28.513	0.717
Non-forest lands (i.e., fire breaks, sands, sparse vegetation, built up area, etc.)	2.833	0.071
Total	39.78	1.00

It was estimated that 30% of the forested area affected by fire were covered by young forests (less than 40 years), 34% were middle-aged (41-60 years) and 28% pre-mature (61-80 years) forests, remaining 8% represented mature (over 80 years) forests. This age characteristic of forests damage reinforces the statement of low resistance of these forests to fires (survival), as resistance to cambium kills is dependent on normalised bark thickness [40]. In terms of species composition 88% of damaged forests by stock were pine forests (4.75 mill. m^3), 5% were birch forests (0.28 mill. m^3), 2% were oak forests (0.15 mill. m^3) and 5% other tree species (0.29 mill. m^3).

Fire Severity

Field-based on CBI and GeoCBI indices have been assessed burn severity. The examples of the areas of different degrees of damage and the corresponding CBI and GeoCBI values are shown in Figure 2.

a) b) c)

Figure 2. Examples of three levels of fire severity assessed based on CBI and GeoCBI indices: (a) high; (b) moderate; (c) low

According to the results of field surveys, the indices of pine plantation damage in each test plot were determined. Summary data of the results of field surveys within individual strata are presented in Table 4. Detailed information on each site is presented in [41] Annex 2.

Table 4. Statistics of damages within the stratum

Code of the strata	Number of plots	CBI			GeoCBI		
		Mean	Range (min/max)	Skew	Mean	Range (min/max)	Skew
1	25	2.60	1.2/3.0	-1.62	2.30	1.2/2.9	-1.34
2	13	2.34	1.1/3.0	-0.99	2.13	1.1/2.6	-0.98
3	17	2.69	1.1/3.0	-2.19	2.43	0.9/3.0	-2.17
4	4	2.13	1.2/3.0	-0.19	1.95	1.1/2.6	-0.92
5	6	2.42	1.1/3.0	-1.11	1.95	1.5/2.6	0.25
6	3	2.07	1.0/2.8	-1.39	2.07	1.0/2.8	-1.39

The highest intensity of forest damage is observed in stratum 3, which is characterised by low soil moisture – pure pine plantations in very dry sites on top of sandy arenas. The lowest intensity of damage is in stratum 4, which is due to the species composition of forests – the presence of deciduous species and higher soil moisture - fresh, moist, and wet conditions [37]. Strata 5 and 6 characterise damage to non-forested areas, which has less negative effect compared to forest losses. It was noted that the CBI index tends to have higher values in forest landscapes than its geometrically modified version, i.e., GeoCBI index. However, the inclusion of the FCOV in GeoCBI calculation could have positive effect on precise estimation of forest damage using remote sensing-based approaches.

The data obtained in this study promotes application of remote sensing approaches for further mapping fire damage. Specifically, field-validated data collected across the gradient of fire severity and within various landscapes (i.e., forested, unforested) are essential to calibrate satellite-derived burn severity metrics and link their values to field-based indices [16; 42]. The authors of this paper believe that apart from the fires under study, the prepared spatial data set can be used to effectively map burned landscapes throughout the territory of the region. Availability of such maps are necessary to support the forest restoration strategy.

The degree of soil damage according to the BAER methodology [21] has shown an indirect relationship between the intensity of the fire and its impact on the soil [41] Annex 1. In general, only two degrees of soil damage were recorded during the field survey, i.e., low and medium. In most cases, the soil damage was characterised by the combustion of forest understory while structural changes in the soil were not detected. Notably, this survey was delayed for six months after the last fire, and therefore some soil characteristics could not be recorded on the site (e.g., water repellence). Nevertheless, the authors of this study agreed with the conclusion of Parsons [21] on the limitation of the BAER methodology to map the effect of fires on vegetation.

Conclusions

This study highlights the impact of the extreme fire events in the Luhansk oblast of Ukraine in 2020. The publication describes a method for field data collection to evaluate levels of forest damage affected by the fire. The results provided in this paper are preliminary, suggesting that the data in this study will provide information on the relationship between key forest characteristics and fire intensity observed remotely to map burned areas. However, field research allows assessing the levels of damage to pine forests that are dominant in the research area. This study showed that the FCOV component of the GeoCBI is important while damage to forest vegetation is characterised. In terms of further use of remote sensing-based approached, the CBI index potentially could overestimate the fire severity levels for forested landscapes. Based on the CBI and GeoCBI, the authors also found empirical evidence that fire severity depends on forest composition and tends to be higher in coniferous landscapes. This is the first use of field-based fire severity in Ukraine which can be used to assess fire damage in similar conditions. The results of these field assessment of forest fire severity can be used to estimate the fire severity of all damaged areas in the region using remote sensing methods.

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Польова перевірка індексів ступеня пошкодження пожежами лісів в Луганській області, Україна

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Анотація. Оцінка ступеня пошкодження внаслідок лісової пожежі є основою після пожежного ведення лісового господарства. Методи дистанційного зондування Землі (ДЗЗ), дозволяють надійно окреслити периметри пожежі, проте детальніша оцінка пошкоджень лісових насаджень потребує польових обстежень для верифікації та коригування даних, отриманих методами ДЗЗ. Оцінка ступеня пошкодження лісу є корисною практикам для обґрунтування проєкту рубок пошкоджених лісів та методів лісовідновлення. Отже, метою дослідження є верифікація різних підходів щодо польової оцінки ступеня пошкодження лісів пожежами. Дослідження виконано на прикладі лісів Луганської області, в яких у 2020 році відбулися великі пожежі. Для оцінки ступеня пошкодження лісових насаджень використовувалися комплексний індекс вигорання (CBI) та геопросторовий комплексний індекс вигорання (GeoCBI). Також для оцінки ступеня пошкодження ґрунту використано методику реагування на надзвичайні ситуації на пройдених пожежами територіях (BAER). Для окреслення периметрів пройдених пожежами територій використано супутникові знімки PlanetScope. Наклавши отримані периметри пожеж на базу даних таксаційної характеристики лісів отримано характеристики всіх ділянок вкритих лісом та невкритих, які були пройдені пожежами. В межах встановлених контурів пожеж, всі ділянки було розділено на 6 страт, для оцінки пошкодження в різних типах земельного покриву. Загалом за методиками CBI, GeoCBI та BAER обстежено 73 пробні площі для оцінки інтенсивності пошкодження, які пропорційно розподілені між різними стратами. Встановлено, що пожежами було пройдено загальну площу 39782 га, з яких 21,2 % вкриті лісом території. Серед пройдених пожежами лісів 78 % становлять соснові деревостани. Найвищі рівні інтенсивності пошкодження встановлено в чистих соснових насадженнях у дуже сухих умовах, а найнижчі в листяних лісах у вологих умовах. Середні індекси інтенсивності пошкодження варіювалися в межах окремих шарів кожної ділянки, тому геопросторовий комплексний індекс вигорання, який враховує частку кожного шару на ділянці у більшості випадків був меншим за комплексний індекс вигорання (CBI>GeoCBI), що важливо враховувати під час оцінки інтенсивності пошкодження за допомогою методів ДЗЗ. Методика BAER має менше значення в оцінці інтенсивності пошкодження, оскільки невстановлено значущої залежності між ступенем пошкодження ґрунту та інтенсивністю пошкодження рослинності. В результаті цього дослідження представлено набір просторових даних вибіркових ділянок, які можуть використовуватися для калібрування підходів, які використовуються для картографування інтенсивності пошкодження в регіоні дослідження

Ключові слова: польові індекси інтенсивності пошкодження, пошкодження лісу, пройдена пожежею територія, стан ділянки

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Assessment of Model Grass Plots of the City of Kyiv in Eco-Conditions of Anthropogenic Load

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Abstract. Urban heat islands (UHI) and rapid urbanisation create new health risks for residents of urban territories. The authors consider lawns as an eco-stabilising factor of the urban environment and an element of ensuring the environmental safety of the capital. The purpose of this study was to determine the qualitative state of lawns to the factors of the urban ecosystem and their thermoregulatory function. To determine the impact of anthropogenic factors on research objects, the study assessed the amount of emissions into the atmospheric air from stationary and mobile sources, satellite maps of the intensity of nitrogen dioxide emissions (NO_2) and sulphur dioxide (SO_2) in the city's air basin, heat distribution, and normalised difference moisture index (NDMI). To assess the condition and quality of lawns, the methods of assessing the grasslands of A. A. Laptev (1983) and an unmanned aerial vehicle (UAV) were used. It was established that the results of the evaluation of lawn coenoses using the method of O.O. Laptev and UAV are correlated (r=0.87). Lawn areas that were rated as in "satisfactory condition" are characterised by a higher temperature on the heat map and lower NDMI values. Indicators of lawn cover that were rated as in "good condition" correlate with surface temperature and NDMI. The difference in surface temperatures over the area of the experimental sites reaches 5°C and depends on the objects surrounding the perimeter. It was established that lawn areas adjust the thermal mode of the urban system in the warm period of the year, and reduce the temperature of the asphalt surface by about 0.5°C, and together with flower and woody plants – by about 0.9°C. The study results improve the understanding of the physiological effects of heat stress on lawn areas, which allows developing practical strategies for managing urban green spaces with limited water resources and anthropogenic loads

Keywords: decorativeness, projective cover, heat island, urban ecosystem

Introduction

According to the "Strategy of Development of the City of Kyiv until 2025", one of the priority goals is to ensure environmental safety in the capital and reduce the adverse environmental impact [1]. Green spaces, including lawn coverings, are eco-stabilising buffer components of the urban ecosystem, they constitute an inseparable component of landscaping systems for any city [2-4]. Rapid urbanisation, technogenesis processes, and climate change are a prerequisite for environmental changes in species optimums, reduced biodiversity and ecosystem sustainability [5-7]. Lawn coenoses constitute the dominant elements of urban landscaping worldwide and account for up to 50-70% of urban

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green spaces, which does not directly depend on the climatic conditions of the region [8; 9]. New research also points to the social functions of green spaces in the context of COVID-19 [10; 11]. Lawn coverings are the easiest and fastest way of landscaping in cities [12]. The study of the influence of anthropogenic load factors on the city's lawn areas as the main elements of urban landscaping, including near roads, will allow investigating their eco-stabilising functions and improve the living conditions of citizens. In the context of irreversible large-scale global climate changes, technogenesis, and urbanisation, new factors are emerging in populated cities that directly or indirectly affect plants, including UHI and air pollution. It was found that the frequency, intensity, and duration of heat waves constitute unstable indicators that change and worsen over time due to global climate change [13]. It was recorded that an increase in vegetation cover by 10% reduces the temperature of the urban surface by about 1°C during the day [14]. Thus, scientists have found that urban lawns reduce the impact of UHI on the urban ecosystem [2; 12; 15]. The 20th century was described by the emergence of a new ecological factor due to the rapid development of Industry – anthropogenic environmental pollution. According to the data from [16], only in the 1920s – 1930s did the scientists begin to study the issues of plant resistance to aerotechnogenic emissions and only in the second half of the 20th century these studies became large-scale. Furthermore, air pollution of urban ecosystems with substances such as NO_2, SO_2, carbon monoxide (CO) is a problem affecting not only the quality of life of urban residents, but also the sustainability and functioning of the urban ecosystem in general [17-19]. Plants as producers of ecosystem services in the context of reducing the impact of air pollution as a new anthropogenic factor in cities began to be studied on a large scale in the 1990s [20-22].

According to their functional purpose, lawns are divided into decorative, special, and sports purposes, where each group has certain characteristics and requirements for creation and maintenance [23]. It is well-known that the quality indicators of lawns are influenced by soil and climatic conditions, agricultural techniques of maintenance and species composition, but the issue of the state and quality of lawns in territories with a considerable anthropogenic load, such as the city of Kyiv, is understudied and relevant at the same time in the context of investigating lawn coenoses in urban ecosystems. Likewise, it is well-known that increasing the quantitative and qualitative state of vegetation in the city reduces the temperature regime of the air and surface [24-26]. Studying the impact of indicators of technogenic load of the urban ecosystem on plants allows reducing the complexity of the urban ecosystem to a manageable level in the context of making constructive decisions in the formation of green spaces [27-29]. Furthermore, to assess the state of lawn coenoses and decide on carrying out agrotechnical works, landscape industry workers need to seek innovative ways to monitor such objects that do not require prolonged time costs [30]. The purpose of this study was to assess the quality condition of lawns and their temperature-regulating properties, which grow localised near roads and transport interchanges. To perform this study, the authors identified the following tasks: 1) to identify model lawn areas with anthropogenic load near transport interchanges in the territory of Kyiv through the analysis of the amount of emissions into the atmosphere from stationary and mobile sources, satellite maps of the intensity of NO_2 and SO_2 emissions; 2) to analyse the distribution of NDMI indicators in experimental areas; 3) to assess the condition and quality of model lawn areas using various methods; 4) to analyse data and compare it with other international studies.

Materials and Methods

To conduct experimental studies of lawns assessment, the authors used the classical method of O. Laptev's assessment [23] and modern techniques of remote sensing of the Earth (remote sensing). To perform the tasks set, model grass plots were selected, which are located on the territory of four administrative districts of Kyiv with an anthropogenic load. The authors have identified four model lawns located on Odeska Square (50°22'12.0"N 30°27'31.0"E), Darnytska Square (50°26'32.0"N 30°37'33.0"E), along Heneral Almazov Street and L. Ukrainka Square (50°25'48.9"N 30°32'28.0"E), Kharkivska Square (50°24'08.0"N 30°40'59.0"E) and estimated during the growing season in June-August 2018. Using an UAV, the authors determined the areas of model lawns. All model lawns do not have an irrigation system, except for the plot located on the territory of L. Ukrainka square.

According to the Main Department of Statistics in Kyiv, mobile sources occupy a considerable place in the urban ecosystem, and therefore road transport is key in air pollution in the metropolis [31]. Furthermore, in 2018, emissions from mobile sources accounted for over 80% of the total amount of substances released. Results of the emission assessment in Figure 1 is presented by indicators of emissions from road transport and calculated based on data on the final use of fuel by road, given in the energy balance of Ukraine.

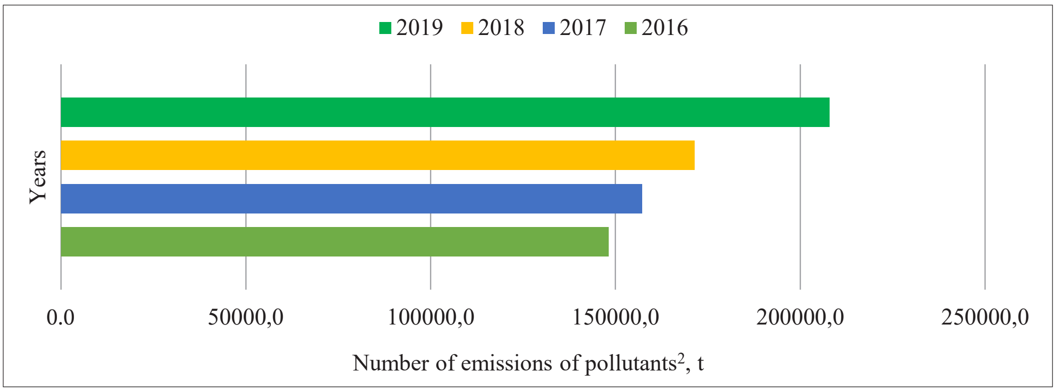


Figure 1. Emissions of pollutants into the atmosphere from mobile sources in Kyiv (2016-2019) [31]

Statistical data allow the districts of Kyiv to be divided by the amount of emissions of pollutants from stationary sources of pollution (Fig. 2). Thus, the leaders in atmospheric air pollution from stationary sources are Pecherskyi, Holosiivskyi, Desnianskyi, and Darnytskyi districts, where research objects are located.

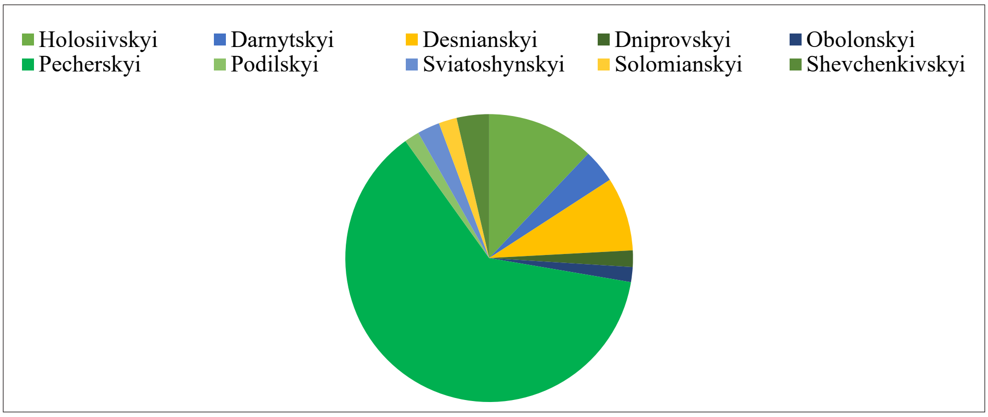


Figure 2. Emissions of pollutants into the atmosphere from stationary sources of pollution by district (2018, amount of emissions of pollutants[2], t) [31]

The heat map of Kyiv demonstrates a heterogeneous temperature distribution, where the temperature regime varies from 27°C to 38°C, which, for its part, forms UHIs mainly in the central part of the city (Fig. 3). The map was developed based on Landsat-8 satellite images with a resolution of 30*30 m. A heat map of Kyiv was provided by the LUN.Misto.ua platform's employees to conduct this study [32]. All experimental lawn coverings are located in areas with a UHI with a temperature regime of 30°C.

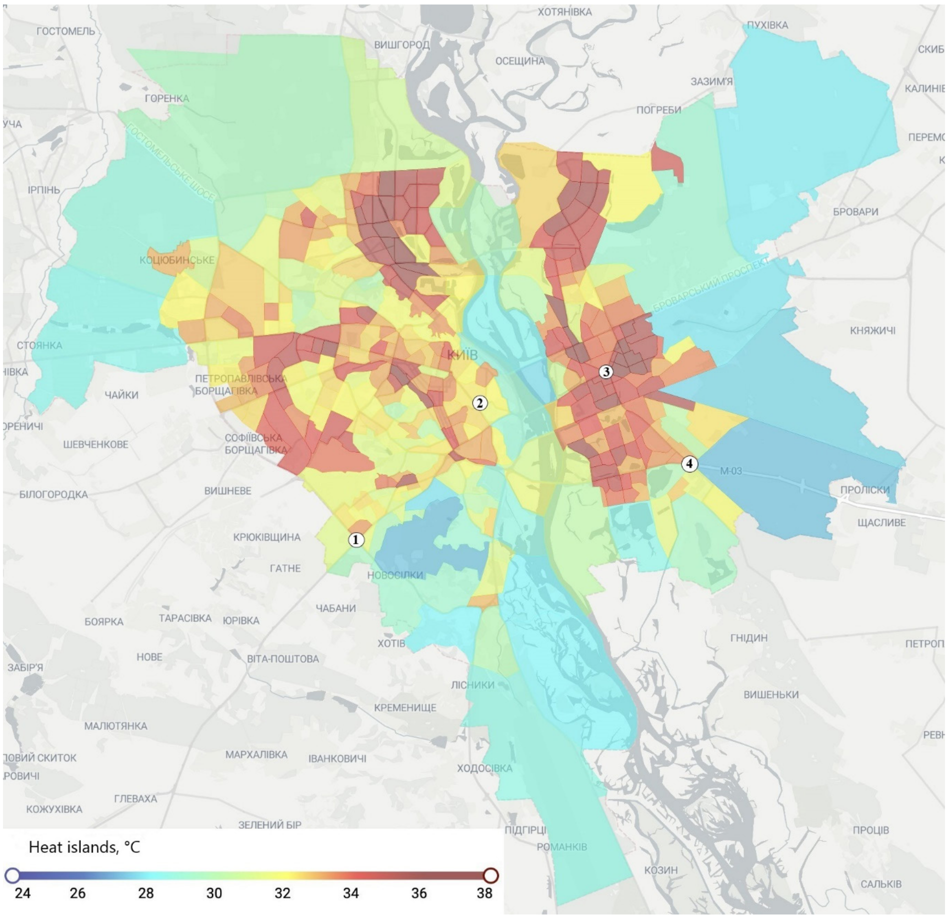


Figure 3. Heat map of Kyiv (2018) (Landsaft-8, LUNMisto 2018) where: 1 – Odeska Square; 2 – Pecherska Square; 3 – Darnytska Square; 4 – Kharkivska Square

Qualitative assessment of the state of lawn coenosis was carried out on a 30-point scale of O.O. Laptev's comprehensive assessment of lawns [23], which includes indicators of the quality of the structure of lawns and general decorative properties (Table 1).

Table 1. Thirty-point scale for comprehensive assessment of the quality of lawns

Assessment of the quality of the structure of lawns on a six-point scale	Assessment of the overall decorative effect of the lawn on a five-point scale	Overall maximum assessment of the grassland quality	Quality indicator of lawns
6	5	30	Top quality (superlawn)
5	5	25	Excellent
5	4	20	Good
4	4	16	Satisfactory
3	3	9	Mediocre
2	2	4	Bad

Source: developed by the author based on the study [23]

The overall decorative effect of the lawn cover was assessed on a five-point scale, determining the degree of soil closure by shortened vegetative and generative organs of plants [23]. At each experimental facility, the authors of this study selected 15 experimental sites and determined the average values. According to the chosen methodology, five points were assessed for the projective coverage of lawns with a closed-diffuse placement of plants and the degree of soil coverage within 90-100% of the total area. According to the closed-mosaic placement of shoots, the projective cover varied within 70-80%, which was estimated at four points. Lawn coenoses with mosaic-group placement of shoots within 50-60% were estimated at three points. Lawns with projective coverage indicators of less than 50% with separate-group placement of plants were estimated at two points and 15-20% with single-separate – one point.

The authors of this study evaluated the build quality of the lawn coenoses on a 6-point scale according to the number of shoots per 100 cm^2 and provided an evaluation according to the indicators of the climate zone [23].

To speed up the process of determining areas covered with lawns, flower beds, and hard surfaces, remote sensing methods were used involving UAV surveys and interpreting the survey results in the ArcGis 10.2 environment. Before the start of filming, the route of movement of the UAV was planned with the determination of the flight altitude, task completion time, based on the area of the landscape object, the focal length of the camera, and the necessary detail. When laying a route, adjacent images, according to the requirements of aerial photography, must have longitudinal (minimum value 56%) and transverse (30-40%) overlaps, which are achieved by setting the required filming interval and combining neighbouring routes [33]. After adjusting all the necessary settings and calibration of the quadcopter, a flyby of the research object was performed at an altitude of 100 m with orthogonal photographing of its territory. Orthotransformation of photographic material was performed in the UTM coordinate system on the WGS84 ellipsoid. Additionally, to improve the accuracy of the obtained materials, external orientation of images was carried out according to previously recorded points with known coordinates that are clearly visible in the images. Each pixel of the image provides information about the spectral characteristics of the lawn cover, its texture, viability, and general condition of plants or the absence of lawn. Furthermore, processing the results of such studies using a geoinformation system allows classifying pixels or their spatial aggregates into diverse groups, which allows determining the condition of lawn coverings, their area, and the closeness of the lawn. The developed method for evaluating the lawns makes provision for three assessment scales, which, based on the results of photogrammetric processing of survey materials, allow distributing the lawns in three states: good, satisfactory, and unsatisfactory [34].

To analyse the factors affecting the research objects, maps of satellite surveys of the intensity of NO_2 and SO_2 emissions were analysed, which were obtained using the Sentinel-5P satellite system and the TROPOMI processing system for NO_2 and SO_2. The humidity index (NDMI) was obtained using the Sentinel-2 satellite system and calculated using the formula . The NDMI index is used to monitor the water content in the lawns at objects under study, where indicators from -0.2 to 0.4 indicate water stress in plants.

Statistical processing of the results and correlation analysis were performed using MS Excel software.

Results and Discussion

In 2017, it was recorded that the annual limit values of NO_2, which are established by the European Commission Directive 2008/50/EC were exceeded in almost 20 European countries [35]. Furthermore, the highest rates of NO_2 are recorded in 86% of cases at road stations [36]. The results of the analysis of the intensity of NO_2 emissions into the air basin of the city of Kyiv demonstrate the heterogeneity of its distribution on the territory of the city, which became one of the decisive factors in the selection of experimental objects (Fig. 4). Notably, NO_2 is found in automobile transport exhaust gases and fumes from thermal power plants. Considering that the lawns under study are located directly near roads and road transport interchanges with heavy automobile traffic, even in conditions of different directions of movement of air masses on different days of assessment, satellite maps clearly demonstrate a tendency to accumulate NO_2 over research areas, especially in the central part of the metropolis. The highest rates were recorded in July on the territory of Darnytska Square (9.0 E-5 mol/m^2), Heneral Almazov Str. and L. Ukrainka Square (6.25 E-5 mol/m^2).

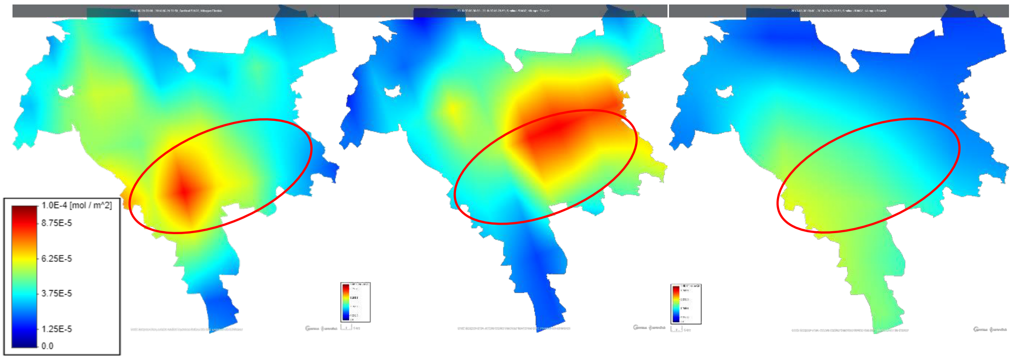


Figure 4. Intensity of NO_2 emissions into the air in the territory of Kyiv (Sentinel-5P 2018-06-29; 2018-07-06; 2018-08-30)

SO_2 can enter the air both naturally and anthropogenically, but approx. 70% is of anthropogenic origin [37]. Sulphur-containing compounds play a crucial role in growth processes, and therefore, in lesser amounts, are absolutely harmless to the plant and, conversely, are characterised by a positive effect. However, in conditions of long-term excess of SO_2 content in plants, processes of decreasing physiological activity begin [38]. The results of the analysis of maps of the intensity of emissions of SO_2 into the air on the territory of objects under study show that in July 2018 alone, on the territory of Darnytska Square, there was a slight excess of SO_2 emissions (0.1 E-5 mol/m²) in comparison with other areas under study (Fig. 5).

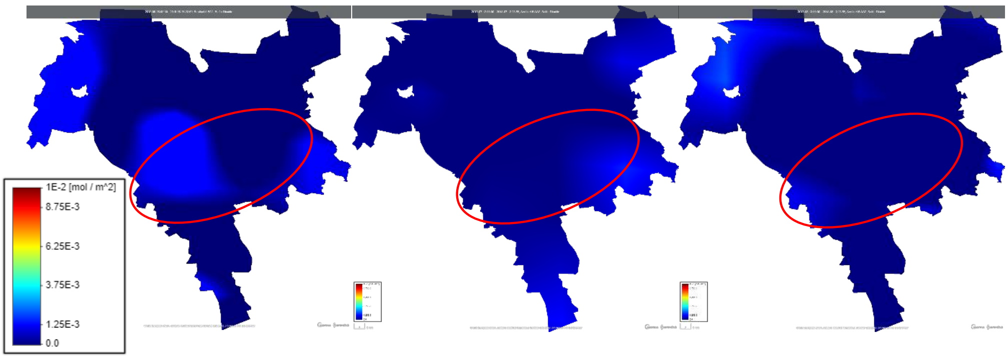


Figure 5. Intensity of SO_2 emissions into the air in the territory of Kyiv (Sentinel-5P 2018-06-26; 2018-07-12; 2018-08-13)

The results of assessing the overall decorative effect of lawns show low indicators of the quality of lawn coenoses near roads (14-18 points). Notably, all objects under study lack an irrigation system, which also directly affects the indicators of decorative properties, condition, and quality of lawns. Photo examination revealed areas where the vegetative organs of herbaceous plants did not cover the surface, the lawn changed colour from green to yellow. This is primarily conditioned upon high-temperature stress and anthropogenic loads on the territory of objects under study. Analysis of research data using UAVs indicated that the lawn on Odeska Square occupies an area of 36,312 m². The average lawn quality indicator is rated as "mediocre" and is 14 points according to the integrated lawn assessment scale. It was found that 75% of the area of the lawn coenosis in terms of the quality of the structure of lawns varied from 2 to 4 points, and only 25% was estimated at 5 points (Fig. 6). The average indicators of projective coverage were 3.6 points and approx. 13% was estimated at 5 points as closed-mosaic, which indicates low indicators of closure of the lawn, which is probably also caused by anthropogenic load on plants.

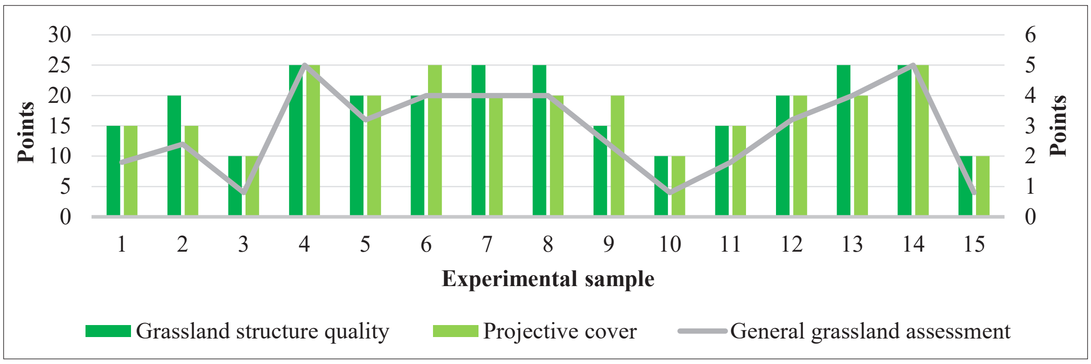


Figure 6. Results of evaluating lawn surface indicators on the territory of Odeska Square

According to the results of field studies, it was revealed that the lawn on the territory of Heneral Almazov Street and L. Ukrainka Square is in satisfactory condition (Fig. 7). Indicators of the quality of the structure of the lawn were characterised mainly by 4-5 points, and the projective cover varied from 2 to 6 points. Analysis of the research results indicated that only one sample was rated at 6 points, where the number of shoots was 124 pcs. per 100 cm^2. Projective cover was mainly evaluated as closed-mosaic and mosaic-group, which corresponds to 3 and 4 points on a 5-point scale.

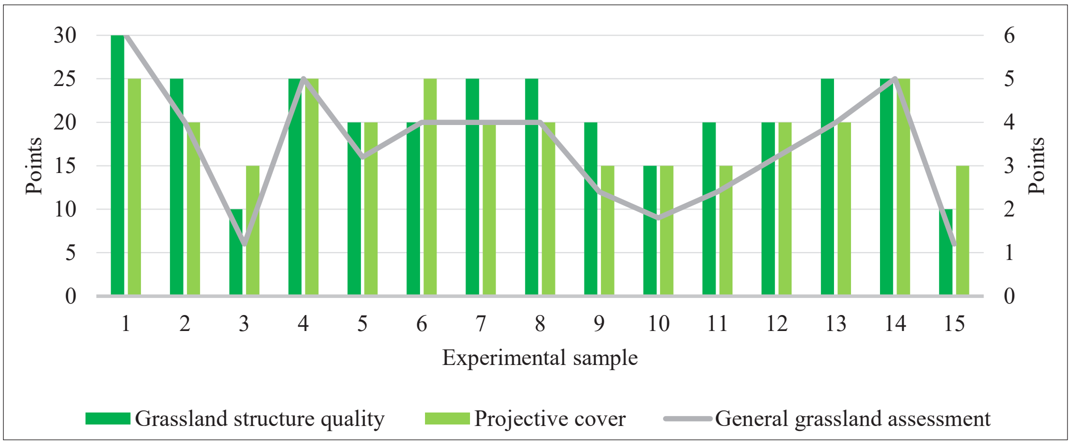


Figure 7. Results of assessment of lawn covering indicators on the territory of Heneral Almazov Street and L. Ukrainka Square

According to the results of the study, the lawn on the territory of Darnytska Square is described by the highest indicators of lawn quality and amounts to 17.5 points, which is equivalent to a satisfactory indicator (Fig. 8). The area of lawn coenosis is 10,347 m^2, where 75% in terms of the quality of the lawn structure and 50% in terms of the overall decorative effect of the projective cover were estimated at 4 points.

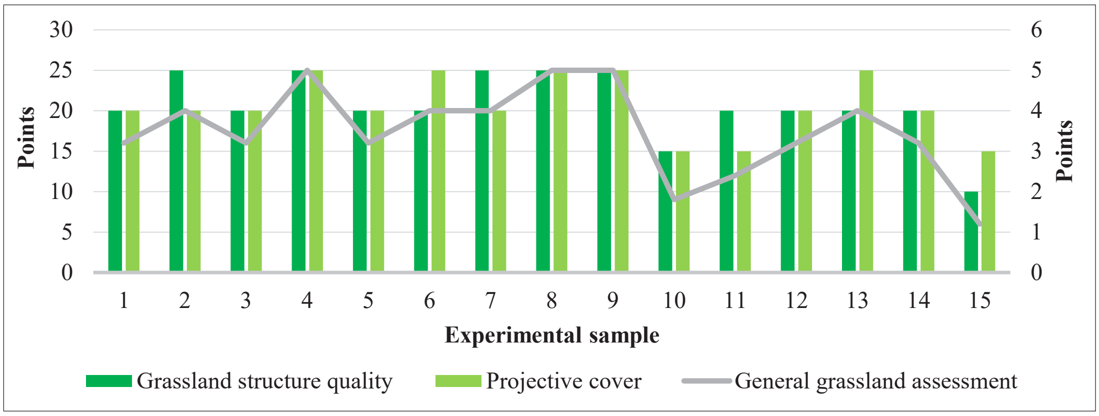


Figure 8. Results of assessment of lawn indicators on the territory of Darnytska Square

The lawn on the territory of Kharkiv Square was described by rather low indicators of the quality of the structure of the lawn and approx. 27% was rated at the lowest score, where there were less than 20 pcs. of shoots per 100 cm^2 (Fig. 9). Almost 50% of the experimental lawn coenosis was described by a closed-mosaic nature of the composition of the lawn and was estimated at 4 points.

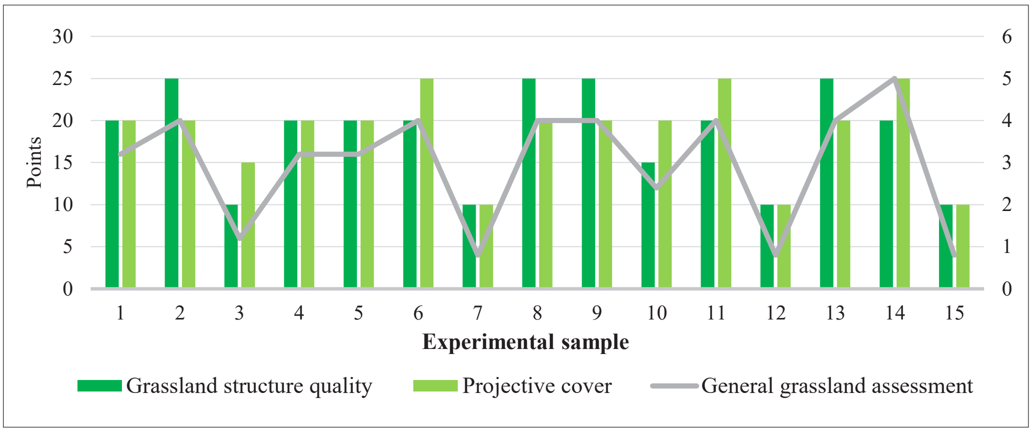
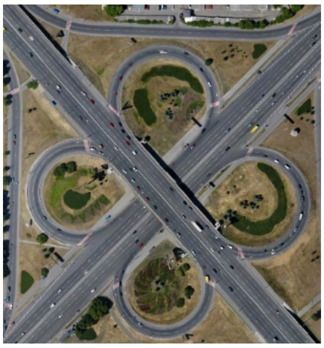


Figure 9. Results of assessment of lawn indicators on the territory of Kharkivska Square

The first stage of assessing the state of coenoses on the territory of objects under study was the differentiation of contours and areas of research lawns and other garden and park elements (Table 2). All experimental lawns do not have an irrigation system, except for the model lawn plot, which is located on the territory of L. Ukrainka Square, which certainly affects their quality indicators.

Table 2. Differentiation of elements of objects under study using a UAV (2018)

Output orthophotoplane	Classification results
Odeska square	
	
Darnytska square	
	
Heneral Almazov St. and L. Ukrainka Square	
	
Kharkivska square	
	

Note: colour symbols for the following elements:

	Remote filming materials		Lawn (unsatisfactory condition)
	Lawn (good condition)		Flower beds
	Lawn (satisfactory condition)		Hard surface

When assessing the lawn coenosis by projective coverage indicators, it was found that most of the grass species that formed the lawn were described by drying of the aboveground part. The authors of this study believe that this may have been caused by high-temperature stress. Table 3 presents the results of evaluating lawn coenoses with a division into quality states – unsatisfactory, satisfactory, and good.

Table 3. Results of determining the areas of research objects based on remote sensing materials

Seq. No.	Name	Area, m²						
		Lawns (condition), m² / %				Flower beds	Hard surface	General area
		good	satisf.	unsatisf.	total			
1	Odeska square	2,197 / 6.1	8,362 / 23	25,753 / 70.9	36,312 / 100	6,960	46,035	89,307
2	Darnytska square	199 / 1.9	3,962 / 38.3	6,186 / 59.8	10,347 / 100	245	19,758	30,350
3	General Almazov Street and L. Ukrainka Square	2,862 / 21.8	1,460 / 11.2	8,770 / 67.0	13,092 / 100	735	41,112	54,939
4	Kharkivska square	3,167 / 5.8	12,979 / 23.8	38,396 / 70.4	54,542 / 100	4,688	47,472	106,702

Thus, data on the qualitative state of lawns in urbanised areas of the city were obtained using various assessment methods [23; 34] and compared using correlation analysis. A correlation was established with r=0.87 upon comparing the total indicators of satisfactory and good condition of the indicators of experimental lawns with the indicators of the overall assessment of the grass plots in points. A low correlation of r=0.3 was found when comparing only the indicators of "good condition" with the indicators of the overall assessment of the lawns. Such results demonstrate the effectiveness of the method of assessing the lawn surface using UAVs, which, apart from assessing the qualitative state of the coenosis, allows differentiating the site according to the quality state.

To determine the causes of low-quality indicators of lawns in the areas under study, the features of the formation of a UHI and the humidity index were additionally analysed. The decisive factor affecting the condition and quality of a lawn coenosis is heat stress. There are three strategies for plant drought endurance (escape, avoidance, and tolerance), but the same species can combine them when adapting to drought stress [39; 40]. Scientists note that the relative importance of each adaptation mechanism depends on the duration of the drought, the severity of the drought, and the grass species specificity [41]. The heat map shows the heterogeneity of the temperature regime of city surfaces and a decrease in temperature indicators in the presence of vegetation or water bodies (see Fig. 3). When comparing the heat map and the NDMI content, a pattern is established – with an increase in the temperature regime, there is a tendency to decrease the NDMI, as well as indicators of the quality of the lawn surface. Thus, the lowest indicators according to the results of the UAV assessment were obtained by the lawn covering located on Darnytska Square (good condition – 1.9%). The results of satellite surveys show the accumulation of the highest temperatures in this area compared to other research objects, where the lowest surface temperature was 34°C, and the highest – 38°C and the presence of a temperature difference on the surface is approx. 4°C (see Fig. 10).

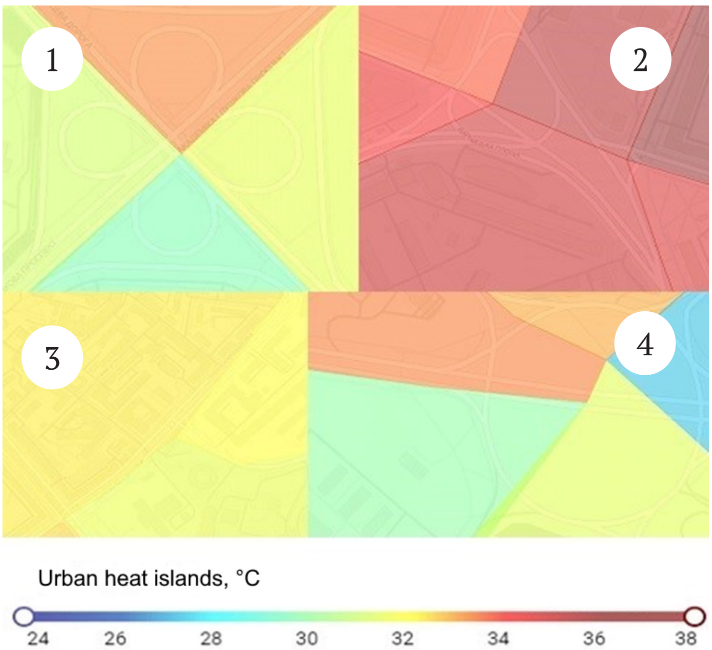


Figure 10. Heat islands on the territory of research objects, where: 1 – Odeska Square, 2 – Darnytska Square, 3 – Henerala Almazova St. and L. Ukrainka Square, 4 – Kharkiv Square (Landsaft-8, LUNMisto 2018)

The NDMI index was used to monitor the water content in the lawns at objects under study, where indicators from -0.2 to 0.4 indicate water stress [42]. It was found that the lowest indicators are typical for the Darnytska Square, where the condition of lawn coverings is estimated as good only approx. 2% and the NDMI did not exceed 0.18. The highest rates of lawns among the objects under study were on Heneral Almazov Street and L. Ukrainka Square, where 21.8% of area was rated as good condition. Such indicators are explained by the presence of lawns with proper agrotechnical care on the experimental territory, which are located near the Administrative Services Centre "Hotovo" and the Central Election Commission of Ukraine. Notably, in places where a lawn at the above-mentioned objects was in good condition, the NDMI indicator was approx. 0.4, and the surface temperature was lower by about 0.5°C (near the Administrative Services Centre "Hotovo", Fig. 11). However, at the object under study on the territory of the Central Election Commission of Ukraine with lawns grow flower and woody plant species, which in the complex also act as an eco-stabilising factor, which allows regulating the thermal mode of the urban ecosystem and reducing the temperature regime of the paved surface by about 0.9°C.

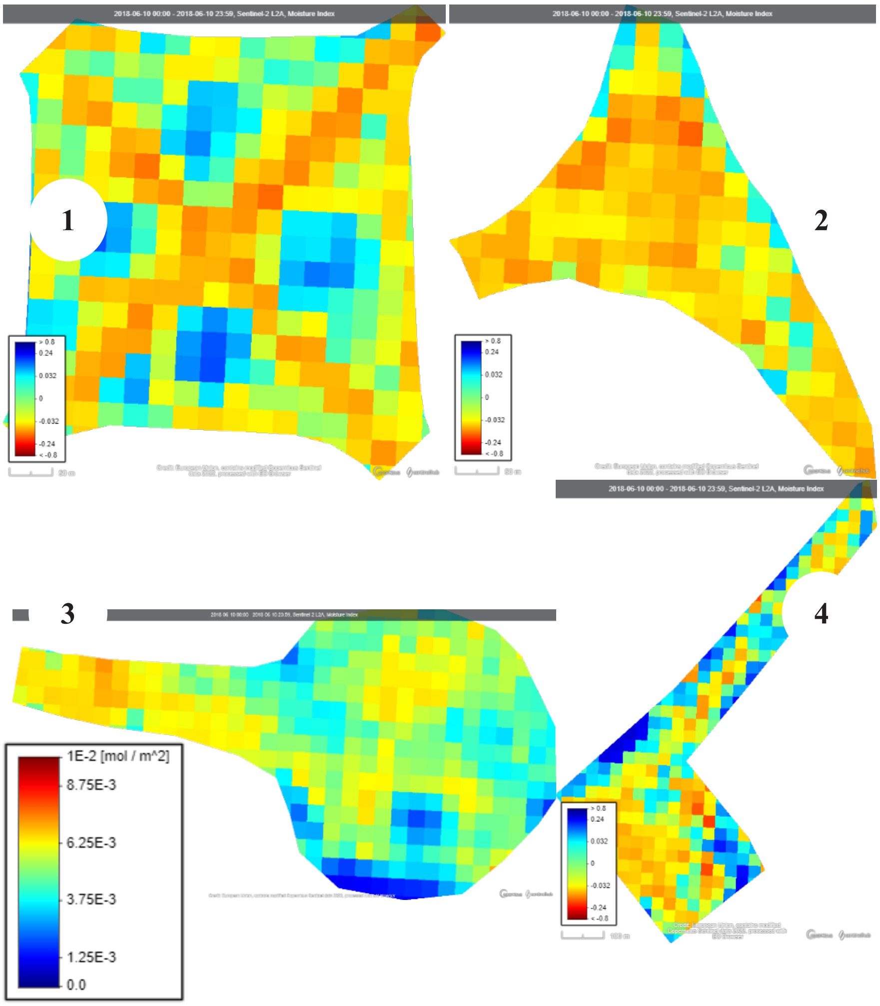


Figure 11. NDMI index on the territory of objects under study, where: 1 – Odeska Square, 2 – Darnytska Square, 3 – Heneral Almazov Street and L. Ukrainka square, 4 – Kharkivska Square (Sentinel-2, 2018-08-11)

Analysis of satellite maps of the NDMI Indicator shows that most of the vegetation on the territory of the research objects was under high-temperature stress. Thus, scientists determine the latent heat of the surface according to the main hydrological process that combines the surface with lawn vegetation and the atmosphere [43]. Notably, on the Odeska and Kharkivska squares a considerable part of the territory is occupied by flower beds – 6,960 m^2 and 4,688 m^2, respectively, which are located in areas with the highest NDMI values (⩾0.7) (see Table 3 and Fig. 11). Interestingly, the largest area of lawns in unsatisfactory condition was found on Odeska and Kharkivska squares. Herbaceous plants that form the lawns under study grow under chronic drought stress due to the lack of an irrigation system (except for L. Ukrainka Square) and the presence of an amount of water below the level of evapotranspiration (ET) [44; 45]. This can be explained by the species composition of the lawns of these areas, where most cereals are represented in comparison with other experimental sites. The aboveground mass of plants under the influence of anthropogenic factors and heat stress is damaged, and the underground mass levels the surface temperature regime due to its high regenerative capacity [46]. Using the example of common meadow-grass, it was found that maintaining transpiration cooling is an essential factor of adaptation in combined conditions of hot temperature and drought due to increased rooting [47]. Perennial ryegrass cultivars show high regenerative capacity after severe drought stress after just 6 weeks [44]. Thus, conclusions can be drawn regarding the specific features of adaptive reactions and adaptations of cereals to conditions of high-temperature stress and anthropogenic factors. ET is characterised by the rate of water use by plants and is expressed as the rate of evaporation. It is established that the evaporation of the upper soil layer increases with a decrease in the density of sod [48]. The data are consistent with the results of studies where the ET of lawns in a humid environment is approximately 40-60% lower than for the same variety in an arid environment [49]. Presumably, the ET processes in cereals under conditions of high-temperature stress increase, which leads to a rapid loss of water depletion in the soil, which is confirmed by the results of tests using UAVs, where the experimental areas of the lawn surface with lower indicators of satisfactory condition correspond to locations on the heat map with higher temperature parameters and lower NDMI. Furthermore, such mechanisms of adaptation to high-temperature stress are manifested in closed stomata [50]. The results of this study on this mechanism of adaptation of lawns are also consistent with experimental data from other researchers [51].

Conclusions

Results of assessing the qualitative condition of model grass plots that grow localised near roads and transport interchanges show low scores from 14 to 18 points out of 30. A correlation (r=0.87) was established upon comparing the total indicators of satisfactory and good condition of the indicators of experimental lawns with the indicators of the overall assessment of the grass plots in points. The statistical data demonstrate the effectiveness of the method of assessing the lawn surface using UAVs, which, apart from assessing the qualitative state of the lawn coenosis, allows differentiating the site according to the quality state. The use of UAVs in the assessment of lawns can serve as an express method for landscape industry workers, which allows quickly and efficiently classifying and identifying areas requiring complex restoration or added agrotechnical works. When comparing the heat map and the NDMI, a pattern was established – with an increase in the temperature regime, there is a tendency to decrease the NDMI, as well as indicators of the quality of the lawn surface.

Thus, the lowest indicators according to the results of the UAV assessment were obtained by the lawn covering located on Darnytska Square (good condition – 1.9%) and was described by the accumulation of the highest surface temperatures among the objects under study. It was recorded that the difference in surface temperatures at the experimental sites was up to 5°C and depend on the presence of buildings, vegetation, water bodies, and the intensity of automobile traffic. The results of the research showed that model lawns are described by temperature-regulating properties in the warm period of the year, reduce the temperature of the asphalt surface by about 0.5°C, together with flowering and woody plants – by about 0.9°C. Such artificially created UHIs, given the temporary loss of plant vitality due to drying out, block the dispersion and neutralisation of toxic substances and require the development of separate recommendations for available methods for restoring vegetation cover and cooling the surface.

The study of the thermoregulatory role of lawns in the city serves as the basis for creating a comfortable city for residents in the centres of UHIs and technogenesis. The question of the influence of anthropogenic factors on the growth and development of herbaceous plants is still understudied and needs to be clarified.

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Оцінювання модельних трав'яних ділянок міста Києва в екоумовах техногенного навантаження

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Анотація. Міські острови тепла і швидка урбанізація формують нові ризики для здоров'я мешканців урботериторій. Автори розглядають газонні покриття як екостабілізуючий чинник міського середовища й елемент забезпечення екологічної безпеки столиці. Метою досліджень було визначення якісного стану газонних покриттів до чинників урбоекосистеми та їх терморегулюючої функції. З метою визначення впливу техногенних чинників на дослідні об'єкти проаналізовано кількість викидів у атмосферне повітря від стаціонарних і пересувних джерел, карти супутникових зйомок інтенсивності викидів діоксиду азоту (NO_2) і діоксиду сірки (SO_2) у повітряний басейн міста, розподілу тепла й індексу вологості (NDMI). Для проведення оцінки стану та якості газонних покриттів використано методики оцінки травостою О.О. Лаптева (1983) і безпілотного літального апарата. Встановлено, що результати оцінки культурфітоценозів за допомогою методики О.О. Лаптева та безпілотного літального апарата корелюють (r=0,87). Трав'яні ділянки, які було оцінено як «задовільний стан» характеризуються вищою температурою на тепловій карті та нижчими показниками NDMI. Показники трав'яного покриття, які було оцінено як «добрий стан» корелюють з температурою поверхні та NDMI. Різниця температур поверхонь на площі дослідних ділянках сягає 5 °С і залежать від оточуючих по периметру об'єктів. Встановлено, що трав'яні ділянки регулюють терморежим урбоекосистеми у теплий період року і знижують температуру асфальтованого покриття близько на 0,5 °С, а разом із квітниковими і деревними рослинами – близько на 0,9 °С. Результати досліджень вдосконалюють розуміння фізіологічних наслідків впливу теплового стресу на трав'яні ділянки, що дозволяє сформувати практичні стратегії управління міськими зеленими насадженнями за обмежених водних ресурсів і техногенного навантаження

Ключові слова: декоративність, проективне покриття, тепловий острів, урбоекосистема

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Multifactor Method for Evaluating the Effectiveness of Wood Fire Protection

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Abstract. The problem of using fire-resistant materials for wooden building structures is to ensure their stability and durability when operating in atmospheric conditions, when it is possible to wash out flame retardants and lose fire resistance. The purpose of this study is to identify the indicators of fire hazard of wood, fire-proof coatings and the effect on them of the heat-insulating layer of coke formed, which allow justifying the effectiveness of the fire-resistant coating under the influence of temperature. The study used a comprehensive research method, which consisted in determining the fire-hazardous properties of fire-proof wood and methods for determining the operational properties of wood fire protection. It was found that upon applying a coating based on alkyd-polyurenitan varnish, due to the polymer film formed on the wood surface, the permeability of flame-retardant components decreases. Tests of fire-hazardous features of wood protection from fire have shown that the coating swells under the influence of heat flow and contributes to a significant heat-insulating layer of coke, which prevents oxygen from reaching the wood and, accordingly, hot temperature, which can ignite the wood. In general, the effectiveness of wood protection from fire shown that wood protected from fire belongs to hard-to-burn materials that slowly spread flames on a surface with low smoke-forming ability. The practical value of this paper lies in the fact that the obtained method for identifying the features of wood protection from fire, comprises determining both atmospheric and thermal properties, and allows establishing the operating conditions of fire protection and the use of products and building structures made of wood of a wide range of uses

Keywords: protective equipment, weight loss, wood surface treatment, flame retardant leaching, polymer shell

Introduction

The scope of use of wood and its structures in construction is broad. Considering the fact that these materials and wood products constitute the main combustible materials and conductors of flame propagation, the safety of wood ignition places high demands on fire protection, as well as on the quantity and quality of fire-proof materials. The effectiveness of fire protection of objects for various purposes is increased with the use of fire-proof wood, which meets the requirements of regulatory documents [1; 2].

For fire protection of wood, water-soluble compositions on an inorganic basis are used, forming a ceramic layer on the surface under the influence of temperature and releasing water, and for effective fire protection they require more application [3]. Today, for the fire protection of wood, a coating capable of forming a heat-insulating layer of foam coke, which thermally insulates the surface of the wood, has been widely used on the surface of the building structure [4]. During the swelling of the composition, the components decompose with simultaneous endothermic decomposition of flame retardants and gas-forming agents, which facilitates a dense layer of foam coke, thereby creating fire-resistant properties of the coating [5]. However, with prolonged exposure to elevated temperatures, which reaches over 1,000°C with a developed fire, individual coatings gradually burn out and to increase efficiency, require an increase in the amount of substances forming a more stable layer of foam coke [6]. This is precisely what determines the need to develop research in this area.

The specific feature of modern fire protection of building structures from fire is to create the necessary layer

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of foam on the surface, which thermally insulates the high fire temperature of over 1,000°C and creates a layer of foam on the wood surface, thereby slowing down the heating of the material and transferring wood to the group of hard-to-burn materials. They constitute complex mixtures of organic and inorganic substances described by high foaming ability. But there is no information on how they are used when atmospheric fluctuations change, in particular, temperature and humidity.

The description of the properties of intumescent coatings is described in [7]. This allows evaluating the conducted studies on thermal stability, where the thermophysical model is considered. But issues related to resistance to atmospheric fluctuations when used in outdoor conditions are still unresolved.

The effectiveness of using flame retardant coatings based on organic components is shown in [8], where flame retardants based on polyphosphoric acids and gas-forming agents can change the conditions for the development of the insulating layer of foam coke. The effect of thermal modification, as well as the ability to protect, revealed by the characteristics of combustion, such as weight loss, burning speed, flame spread, was investigated, but no information was provided on how the chemical changes occurring under the influence of these factors take place. Therefore, it becomes necessary to investigate the conditions for reducing thermal conductivity and determine the conditions for the formation of foam coke.

In [9], the behaviour of wood impregnated with organo-inorganic flame retardants is described, the results of research and testing of which were aimed at investigating the technology and compositions that combine fire resistance, thermal conductivity, and manufacturability of protective coatings. A modified binder made based on liquid glass is used as the main part of the developed compositions. The study describes two types of compositions. The first is a porous heterogeneous structure made based on the authors' technology of two-phase structuring and thermal pore spacing. This composition is intended for the manufacture of moulded products. The second composition is used for the manufacture of fire-retardant coatings by monolithic method. In the study [10], methods for evaluating the response indicators of wood to fire treated with flame retardants based on organophosphate substances were discussed. Such wood was used as the facade of buildings, considering the deterioration of ageing. The fire resistance characteristics of wood were investigated, and it was found that the first indicators worsened during the fire response test by more than 12%.

In the paper [11], the effect of modification, as well as flame retardant ability, was investigated, revealed by such characteristics of combustion as weight loss, burning speed, etc.; however, the issues regarding the manifestation of the joint action of the components remain unexplained. The study [12] was conducted to solve the question of the application as a coating containing many fire-resistant compositions from the sludge of industrial effluents. The coating formula was optimised using a response surface methodology based on a central composite design. During the fire resistance test, this sample shows the lowest reverse surface temperature of the sample (only 163°C) among all samples, which indicates excellent fire resistance. Apart from the analysis of fire resistance, the water resistance and thermal stability of fire-resistant coatings are also characterised.

Furthermore, a considerable number of coatings have disadvantages, such as the application of individual components, loss of functional properties with increasing ambient temperature [13]. This indicates that the coating does not always decompose during operation upon temperature and humidity fluctuations.

In [14], the durability of the fire-resistant properties of a transparent fire-resistant coating for a wood structure was investigated using accelerated hygrothermal ageing. The effects of ageing were analysed using morphological analysis and a fire test. The results indicated that after 21 days of ageing, the flame-retardant components gradually surfaced. The coating mostly lost its ability to expand, and the charred layer showed an unstable lamellar structure. The fire resistance of the coating decreased by 43.48% from 23 min to 13 min.

Thus, it was established from literature sources that fire-resistant coatings can be washed out of the wood surface during operation and the parameters that ensure resistance to the loss of fire protection by wood, as well as what affects this process, are not defined.

The purpose of this study was to investigate the compliance of fire-proof wood with both fire-hazardous properties and operational ones.

To achieve this purpose, the following tasks were solved: the specific features of reducing the degree of wood burnout due to temperature exposure to the sample during the application of the coating were established; the operational properties of wood and establishing the compliance of protective compositions were investigated.

The scientific originality of this paper lies in the development of a multifactor method for assessing fire-resistant properties by indicators of flammability, flame propagation by the surface, smoke-forming ability, as well as operational properties as a corrosion effect and fixation of a fire-resistant coating.

Materials and Methods

Research on determining the fire hazard indicators of fire-proof wood was carried out based on the "Fire Safety Testing Laboratory", city of Chernihiv, operational indicators of fire-proof wood were identified at the laboratory at the National University of Life and Environmental Sciences of Ukraine.

The studied materials that were used in the experiment. The study of countering the leaching of a protective agent from wood treated with a fire-resistant composition was carried out on samples of equal-layer wood (Fig. 1).

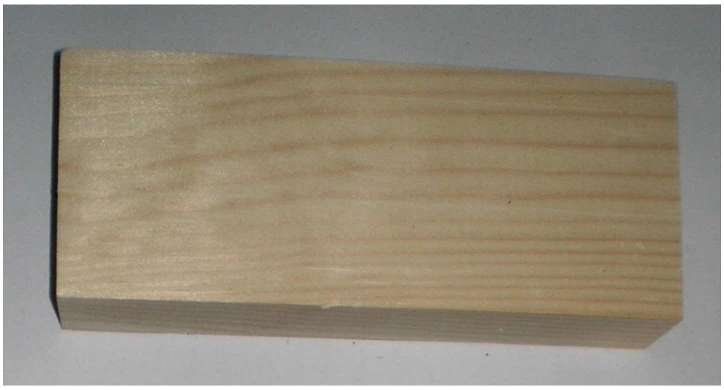

Figure 1. Model samples of pine wood for testing

Samples were treated with a flame retardant for wooden structures ("FAIERVOL-LAK") (Ukraine) in the amount of 580.2 g/m^2; therewith, the thickness of the flame-retardant coating was about 250 microns, which was determined earlier. To increase the water resistance, the samples were covered with a protective finishing varnish "Alkid-Poliuretanovyi Lak" (TM "Kompozyt") (Ukraine) in the amount of 55÷58 g/m^2 [15]. The thickness, respectively, was about 50 microns.

Methodology for determining the properties of samples of fire-resistant wood coating. Studies to determine the compliance of fire-proof wood with the fire-technical classification, namely flammability, flame propagation index and smoke formation, were carried out according tofire safety requirements [1; 2], which are given in the regulatory documentation [16; 17]. To assess the degree of hydrophobisation of wood, a sample of the material is fixed in a test device and exposed to a static layer of water until it penetrates the material (Fig. 2).

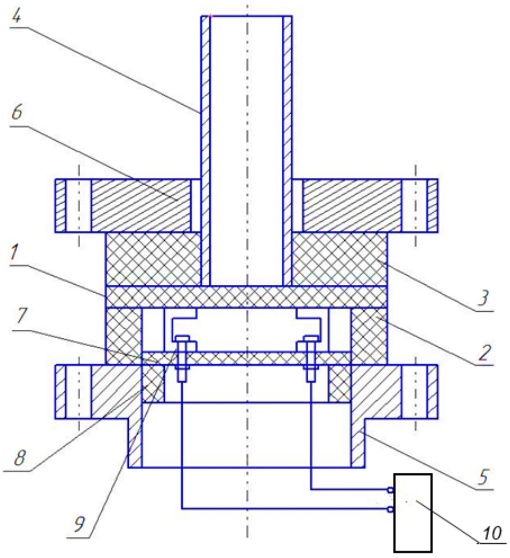

Figure 2. Device for determining the hydrophobicity of fire-proof wood: 1 – test sample, 2, 3 – rubber gaskets, 4 – fluoroplastic pipe, 5, 6 – flanges, 7 – fluoroplastic plate, 8 – ring, 9 – electrodes, 10 – recording device

The criterion for assessing water resistance is the nature of the behaviour of the sample under the action of a static water layer: determination of the increase in the sample after exposure to its surface with water, specific water absorption of the sample, and the degree of hydrophobisation is estimated from the measured values.

In the test setup (Fig. 2), a fire-resistant sample 1 of cellulose-containing material with dimensions of 65x65 mm, a thickness of up to 1.5 mm, untreated and treated, e.g., with a hydrophobic composition, is fixed between rubber gaskets 2 and 3 and sealed with flanges 4 and 5, water in the amount of 200 ml is poured into a fluoroplastic pipe 6 with a diameter of 24 mm. In the lower part of the device, a fluoroplastic plate 7 is installed, which is fixed on one side by a ring 8, and the other touches two electrodes 9 to the reverse part of the sample 1, which are connected to the recording device 10. During the tests, the time of water passage on the return surface of the textile material is recorded, which is evaluated by closing the electrical circuit with fixation on the device.

Characteristics after testing for hydrophobicity of fire-proof wood were determined according to the following coefficient:

$$K_e = 10\left(1 - \frac{\tau_{fp.s.}}{\tau_{h.fp.s.}} \cdot \frac{\upsilon_{h.fp.s.}}{\upsilon_{fp.s.}}\right) \quad (1)$$

where $\tau_{h.fp.s.}$ is the water penetration time of a fire-proof hydrophobised sample; $\tau_{fp.s.}$ is the water penetration time of the fire-proof sample. $\upsilon_{h.fp.s.}$ is the amount of water absorbed by the hydrophobised fire-proof sample, kg; $\upsilon_{fp.s.}$ is the amount of water absorbed by the fire-proof sample, kg.

Determination of the corrosion effect on plates made of flame-resistant coating metals was carried out according to the method [18]. The essence of the method for determining the corrosion effect is to determine the mass loss of a metal plate when interacting with fire-proof wood.

The value of the duration of fire protection of wood was carried out according to the method [19]. The essence of the method for determining the duration of fire protection of wood is to model the diffusion processes of fire-resistant agents artificially and determine the weight loss of fire-resistant wood.

Using the three-factor simplex-central method of planning an experiment in the mathematical environment Statistica 12, statistical processing of the results was performed to determine the weight loss of wood.

The factors of variation were selected as follows: temperature of thermal modification, °C, (factor X_1); amount of coverage, g/m² (factor X_2), the change of which is presented in Table 1.

Table 1. Factors of variation

Factors	Code	Levels of variation			Variation interval
		-1	0	+1	
Number of test cycles	X_1	64	68	72	30
Amount of organo-inorganic coating, g/m²	X_2	350	400	450	10

As the initial parameter (response function), the proportion of destroyed material was chosen, the values of which were recorded on samples exposed to microbacteria.

The experimental planning matrix and its mathematical implementation are presented in Table 2.

Table 2. Experimental matrix and its implementation

Seq. No.	Factors, type		Planning matrix		Response function	
	X_1	X_2	Number of test cycles	Aamount of coverage, g/m²	Y fact.	Y calculation
1	1	1	72	450	8	8.14
2	1	-1	72	350	10	10.54
3	-1	1	64	450	7	6.60
4	-1	-1	64	350	9	9.00
5	1	0	72	400	11	10.33
6	-1	0	64	400	8.4	8.79
7	0	1	68	450	6.2	6.46
8	0	-1	68	350	9.4	8.86
9	0	0	68	400	8.2	8.65
10	0	0	68	400	8.8	8.65
11	0	0	68	400	8.1	8.65

Thus, experimental points with coordinates *+1* and *−1* in a full factorial experiment, where all combinations of factor levels found at the vertices of the hypercube are realised. By writing out combinations of factor levels for each experimental point, a plan for a complete factor experiment of Type 2^3 was obtained, which is showed in Table 2.

Results

The results of studies on the experimental determination of the wood flammability group are presented in Figure 3. It was established (Fig. 3.) that fire-protected wood belongs to construction products of low flammability (F1), and untreated wood belongs to construction materials of high flammability (F4).

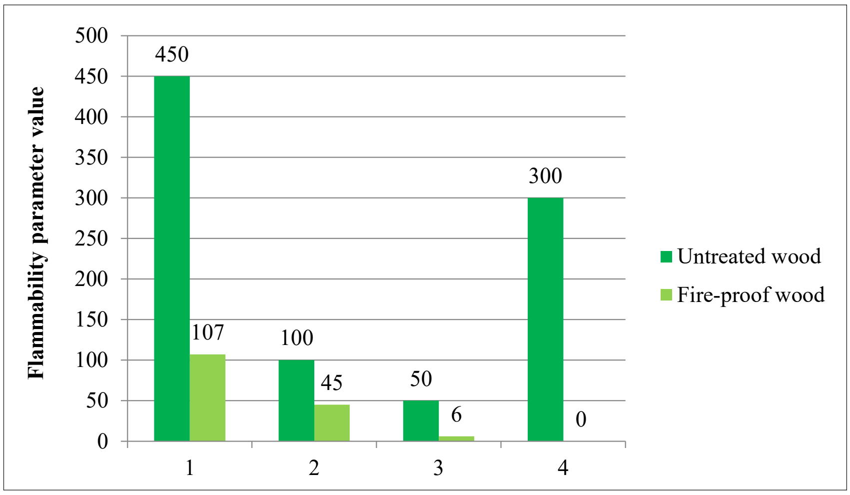

Figure 3. Determination of the flammability group of treated wood): 1 – flue gas temperature (t, °C); 2 – the degree of damage to the samples by length (S_L, %); 3 – degree of damage by mass (S_m, %); 4 – duration of independent combustion (τ, s)

In Table 3 shows the results of determining the flame propagation group by wood. According to the results of experiments, samples of wood with a fire-proof coating are classified as materials that do not spread flames on the surface (RP1), and untreated wood as materials that spread flames on the surface (RP4).

Table 3. Test results for determining the flame propagation group by wood

Wood	Sample combustion time from the start of testing, s	Duration of flame burning of the sample, s	Average value of the damaged part of the sample, mm	Critical surface heat flux density, kW/m²
Unprocessed	36	Over 600	686	4.1
Fire-proof	Missing	Did not occur	39.6	Over 11.0

Figure 4 demonstrates the results of determining the smoke formation coefficient of fire-proof wood. Studies have shown (Fig. 4) reduction of the smoke formation coefficient by more than two times for fire-proof wood samples and their transition from the group of materials with high smoke-forming ability (for untreated samples) to the group of materials with moderate smoke-forming ability (D2).

Figure 4. Results of determining the smoke generation coefficient (D_m, m²/kg) in case of flame burning and smouldering of samples of untreated and coated wood

Studies have shown (Fig. 4) reduction of the smoke formation coefficient by more than two times for fire-proof wood samples and their transition from the group of materials with high smoke-forming ability (for untreated samples) to the group of materials with moderate smoke-forming ability (D2).

Thus, pine wood, which is coated with a fire-proof coating based on organic and inorganic substances ("Faiervol-Lak") with an external coating of one-component alkyd-polyurenitan varnish "Lompozyt", can withstand temperature exposure. According to the fire classification, fire-proof wood belongs to materials of low flammability, a difficult-to-ignite material that does not spread flames on the surface, with a moderate smoke-forming ability.

To assess the degree of hydrophobisation of wood, untreated samples of cellulose-containing materials were first tested. When a hydrostatic column of water acted on the surface (area S=0.00423 m²) of untreated samples, their impregnation with water and intense leakage through the test sample occurred within a time interval of about 300 s. Then the samples were tested, which were treated with hydrophobising agents. During the tests of wood samples protected by a polymer film of the "Gembar" preparation, insignificant impregnation was established for more than 2100 seconds, which considerably exceeds the value of untreated wood by more than 7 times; on the other hand, for samples treated with alkyd-polyurethane varnish, this value increases by more than 42 times (Table 4).

Table 4. Assessment of the degree of hydrophobisation of wood

Samples	Contact closing time when exposed to water τ, s	Amount of water absorbed, kg	Efficiency factor, K
Pine wood without hydrophobiser	306	0.009	–
Pine wood treated with "Gembar" preparation	2122	0.008	8.71819
Pine wood treated with a hydrophobiser based on alkyd-polyurethane varnish	12600	0.001	9.975714

As it was established upon calculating for samples of cellulose-containing materials with insufficient protection of the hydrophobiser, the efficiency coefficient is within 6÷9, and for the protection necessary must be at least 9.5 [20].

The results of determining the corrosion effect of protective agents for wood applied to the sample are presented in Table 5.

Table 5. Value of corrosion destruction of metals in contact with fire-proof wood

Samples	Average specific mass loss rate of a metal plate, g/m²·hour			
	Steel	Copper	Galvanised tinplate	Aluminium
Fire-proof pine wood without hydrophobiser	0.022	0.146	0.034	0.0025
Organo-inorganic coating with hydrophobiser based on alkyd-polyurenitan varnish	No corrosion detected	No corrosion detected	No corrosion detected	No corrosion detected

As the obtained values demonstrate, copper has the greatest corrosion in contact with flame retardants of an organo-inorganic coating, so this indicator must be considered when designing fire protection. The wood protected by an organic-inorganic coating with a hydrophobiser based on alkyd-polyurethane varnish showed no corrosion. Due to the resulting polymer coating, the yield of flame-retardant components that cause corrosion is considerably reduced.

Table 6 demonstrates the results of weight loss of the sample when determining the duration of fire protection of wood.

As Table 6 indicates, fire-proof wood sample treated only with organo-inorganic coating after 60 cycles of testing lost a considerable amount of flame retardants, which led to a weight loss of more than 9% during fire exposure, but the hydrophobiser based on alkyd-polyurenitan varnish provided resistance to fire-proof coating during cyclic tests of about 120 cycles, hydrophobised capillaries and microcracks of the surface, forming a complex water-repellent protective layer, and increasing the thermal resistance of the formed composites.

Table 6. Results of sample weight loss when determining the duration of wood fire protection

Wood sample	Number of test cycles	Average weight of the sample before fire protection, g	Average sample weight, g		Sample mass loss, %
			Before	After	
			Tests		
Treated with an organo-inorganic coating	Control	131.1	144.3	133.9	7.2
	4	132.6	145.9	134.1	8.1
	16	136.8	150.3	138.8	7.6
	28	126.2	138.1	126.1	8.7
	42	125.1	136.7	125.6	8.1
	60	125.8	138	126.4	8.4
	68	135.0	145.8	131.2	9.8
	72	137.4	148.1	134.2	9.4
Organo-inorganic coating with hydrophobiser based on alkyd-polyurenitan varnish	control	132.0	144.2	131.9	8.5
	20	126.9	139.7	127.5	8.7
	40	135.3	147.5	135.1	8.4
	80	130.2	142.1	129.6	8.7
	120	132.1	143.2	128.5	10.2

As a result of the computer solution, regression equations were obtained and ternary surfaces were constructed depending on changes in variation factors (Fig. 5). Regression equation:

$$Y_{calc} = 8.648 + 0.767X_1 - 1.2X_2 + 0.911X_{11} - 0.989X_{22} - 0.0001X_1X_2 \quad (2)$$

Based on the conducted computer modelling, the best value of the number of test cycles and the protective coating that ensures the performance of the task was determined, namely the lowest value of the material mass loss.

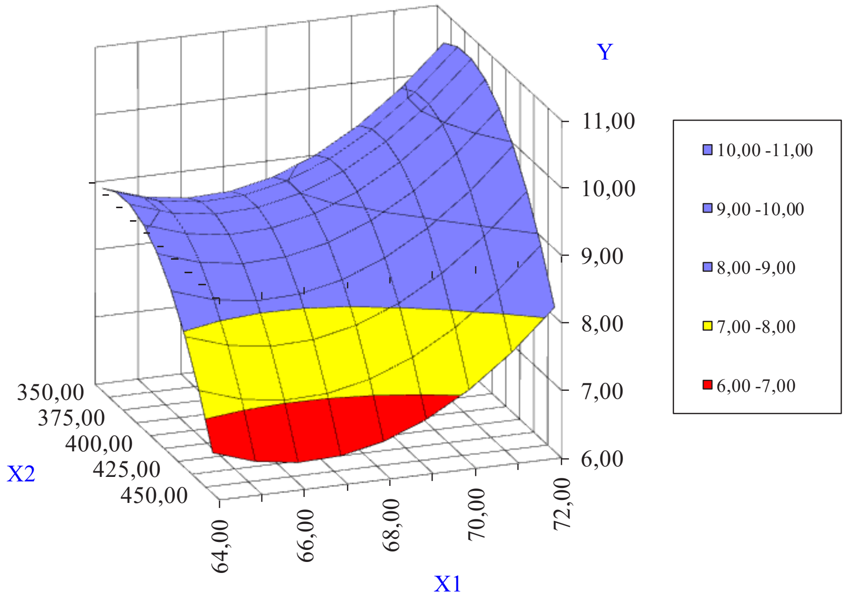

Figure 5. Ternary surfaces of changes in the output parameter depending on changes in variation factors

Discussion

Thus, a change in the fire-hazardous properties of wood upon fire protection has been established. Under the influence of a high-temperature flame and the composition of the coating, as indicated by the results of studies (Table 3, Figs. 3, 4), there is a natural process of reducing the flammability of wood. This is conditioned upon the mechanism of operation of the coating, which lies in the formation of a layer of foam coke, which slows down the heat transfer processes. Notably, protection from fire by the coating leads to the formation of a foam layer on the wood surface and, accordingly, reduces access to combustible components. It is this mechanism of action on wood that serves as a factor in regulating the degree of protection against fire, as well as the effectiveness of water protection of fire-proof wood. Therewith, this mechanism adversely affects the smoke-forming ability of the coating when protected by alkyd-polyurethane varnish. This coincides with the data of the studies [4; 10], where developers also associate changes in the smoke formation process with processing with organic components. In contrast to the results given in [5; 7], the results obtained in this paper suggest the following:

– the main regulator of the reduced heat insulation of wood is not only the formation of a foam layer, but also the thermal resistance of the fire-resistant coating;

– a substantial impact on the transition of wood from a combustible material to a group of materials that burn slowly and slow down the spread of flame by a surface with a low smoke-forming ability is carried out due to treatment with fire-resistant coatings.

Results of improving the performance characteristics of wood protected from fire under the action of a coating based on alkyd-polyurenitan varnish and the formation of a hydrophobic layer (Tables 4, 5) indicate an unambiguous effect of protection with the formation of a strong and dense hydrophobic protective layer on the surface of the material. This uncertainty cannot be resolved in this study, as it requires large-scale experiments to obtain more reliable data. Based on these results, one can state the existence of an interesting pattern associated with the formation of heat resistance to flame and an ability to insulate wood while ensuring effective fire protection.

Conclusions

A study of the fire-hazardous properties of wood with fire-resistant coatings during the formation of a heat-insulating layer of coke was carried out, the mechanism was determined and a change in indicators for fire protection was obtained, which allowed justifying the effectiveness of a fire-resistant coating under the influence of temperature. Tests on model samples of fire-proof wood showed that coatings under the influence of elevated temperatures form a swollen layer of foam coke, contributing to thermal insulation of the wood surface, and preventing the elevated temperatures from reaching the wood and its subsequent burnout. This slows down the smoke formation and combustion of the material. In general, the effectiveness of fire protection of wood, which was obtained by the multifactorial method of determining the operational properties, established that the treated wood belongs to non-flammable materials that slowly spread the flame over the surface and have a low smoke-generating capacity.

The legality of the joint use of hydrophobisers with a fire-resistant coating of wood on particular models of the influence of changes in humidity and temperature was confirmed. Conducted studies on the determination of the degree of hydrophobisation of wood, the corrosive effect of protective agents on metals and the duration of fire protection of wood by keeping them at variable temperature and humidity indicators within wide limits showed that when applying a hydrophobiser, a waterproof layer is formed, which protects wood from the action of moisture and the washing out of flame retardants, namely the capillaries and microcracks of the surface are hydrophobised by a protective polymer film, which increases operational performance.

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Багатофакторний метод оцінювання ефективності вогнезахисту деревини

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Анотація. Проблема застосування вогнезахисних матеріалів для дерев'яних будівельних конструкцій полягає в забезпечені їх стійкості і довговічності при експлуатації в умовах атмосферного коливання, коли можливе вимивання антипіренів і втрата вогнестійкості. Мета проведених досліджень полягає у визначені показників пожежної небезпеки деревини, вогнезахищеними покриттями та вплив на них утвореного тепло ізолюючого шару коксу, що дозволяють обґрунтувати ефективність вогнезахисного покриття при впливі температури. В роботі використано комплексний метод дослідження, що полягав у визначені пожежонебезпечних властивостей вогнезахищеної деревини та методів визначення експлуатаційних властивостей при вогнезахисті деревини. Встановлено, що при застосуванні покриття на основі алкід-поліуренітанового лаку, за рахунок утвореної полімерної плівки на поверхні деревини зменшується проникність компонентів антипірену. Випробування пожежонебезпечних характеристик захисту деревини від вогню показали, що покриття під впливом дії теплового потоку спучується та сприяє утворенню значного тепло-ізолювального шару коксу, який запобігає проходженню до деревини кисню та відповідно високої температури, яка здатна запалити деревину. Загалом ефективність захисту деревини від вогню, показала, що деревина захищена від вогню відносяться до важкогорючих матеріалів, які повільно поширюють полум'я поверхнею з малою димоутворювальною здатністю. Практична цінність полягає у тому, що отриманий метод визначення характеристик захисту деревини від вогню, полягає у визначені як атмосферних, так і термічних властивостей, та уможливлює встановлення умови експлуатації вогнезахисту та застосування виробів і будівельних конструкцій з деревини широкого спектру використання

Ключові слова: захисні засоби, втрата маси, оброблення поверхні деревини, вимивання антипірену, полімерна оболонка

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