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Assessment of ecosystem functions of green spaces as an important component of their inventory in the context of sustainable development of urban landscapes

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Abstract. An important area of research in the context of ensuring the sustainable development of urban ecosystems is the development of theoretical and applied aspects of the possibilities of obtaining information about the ecosystem usefulness of green spaces. The concept of evaluating and paying for eco-services that produce trees and shrubs for the environment and society is characterised by substantial international interest. In this context, it is important to analyse modern tools and techniques that can adequately determine and evaluate the amount of ecosystem services, which was the main goal of the study. In this paper, the possibility of using the i-Tree Eco tools for quantitative and cost determination of the volume of ecosystem services created by park spaces in the green space inventory process is tested. For this purpose, on the example of the prefix part of the Rayivskyy landscape park of the Ternopil region, the measurement of biometric and sanitary indicators of trees during their inventory was conducted, a number of ecosystem services of plants were determined (reduction of pollutants, absorption and sequestration of carbon, oxygen production, and regulation of avoided runoff), the replacement cost of trees was established, the data obtained were analysed, the interpretation of the information received in the form of an interactive electronic map was performed, and the advantages and disadvantages of this process were determined. The study showed that the cost of ecosystem services (in the context of the indicators under study) for the attached part of the Rayivskyy landscape park is 81894 UAH (€3044) per year, and the total replacement cost of the examined plantings is 4486,464 thousand UAH (€166,783). The monetised expression of the ecosystem utility of this plantation creates conditions for improving the understanding of the value of the phytocenosis for urban landscapes. The practical value of the study is the possibility of using its results to improve and

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increase the information content of the green space inventory process, by obtaining information about ecosystem services of trees in quantitative and cost terms to increase the validity of decisions in the field of nature management

Keywords: utility monetisation; replacement cost of trees and shrubs; i-tree Eco, environmental improvement; century-old trees

Introduction

Green spaces are important for ensuring the sustainable development of urban landscapes due to the fact that they can mitigate the negative effects of anthropogenic activities in urban ecosystems by improving the ecological, sanitary, climatic, and aesthetic state of the environment. Tree and shrub stands in the city need regular examinations to ensure proper care, protection from adverse factors and protection to fulfil their important role in optimising the oxygen-carbon balance of the ecosystem, cleaning and improving the biosphere, improving the local microclimate, avoiding runoff, and other ecosystem functions. For this purpose, the inventory of green spaces defined by the Order of the State Committee for Construction, Architecture and Housing Policy of Ukraine No. 134 "On the Approval of the Instructions on the Inventory of Green Spaces in Populated Areas of Ukraine" (2014) should be conducted regularly, once every five years. However, in practice, according to the findings of researchers Y.A. Melnyk *et al.* (2019), D.I. Bidolakh & P.I. Lakyda (2019), in Ukraine, such inventory for urban plantings is performed much less often. In addition, according to D.I. Bidolakh (2020), S.V. Rohovskyi *et al.* (2021) it is conducted in accordance with an outdated methodology and requires updating approaches.

The latest trends in the development of modern technologies, according to many researchers (Lin *et al.*, 2020; Bidolakh, 2020; Croci, Lucchitta & Penati, 2022), open up new opportunities for collecting, analysing, and interpreting information obtained during the inventory of green spaces. One of the important areas of this process is the assessment of the quantitative and cost parameters of ecosystem services of trees and shrubs, which allows for a better understanding of the usefulness and value of green spaces in urban landscapes. Therefore, the combination of processes for obtaining standard information based on the results of inventory on the main quantitative and qualitative indicators of phytolandscapes, the sanitary condition of plants with their biometric data, which are used to determine ecosystem benefits, creates conditions for expanding the scope of application of the obtained materials and increases their value. Therewith, according to the results obtained by N. Stoeckl *et al.* (2023) almost 90% of these utilities are ecosystem services related to natural capital, and more than half are services that are still difficult to monetise.

Along with this, some researchers (Steenberg *et al.*, 2017) recommend considering the vulnerability of green spaces in urban landscapes, which, in the absence of preventive measures, can lead to a decrease in the volume of ecosystem functions performed with a corresponding loss of benefits for residents, urban infrastructure, and natural biodiversity. These volumes also require quantitative and monetised expression to understand the losses that the ecosystem and society will suffer from the misuse of natural resources. Under such conditions, a logical conclusion arises, formulated in the studies of researchers T.P. Ly & H. Xiao

(2016), C.-S. Chan *et al.* (2018), on the importance of establishing a balance between the norms of recreation and the use of useful functions of green spaces, on the one hand, and environmental measures and economic investments in the development of green infrastructure, on the other hand, in the context of the need to ensure sustainable ecosystem development. In general, the critical state of ecosystems at the planetary level, according to the authors (Gaglio *et al.*, 2023), requires, in the light of the Sustainable Development Goal of cities and communities, the immediate adoption of measures aimed at achieving an impact in the environmental field and economic development.

Therefore, the relevance of the paper follows from the need to examine the theoretical and practical foundations of the possibilities of obtaining information about ecosystem services of green spaces and their assessment, considering the benefits that they create for the environment and society.

The purpose of this study was to develop approaches to involve tools for assessing the cost of ecosystem services in the process of inventory of green spaces to obtain, interpret and further present information about the environmental and cost value of green spaces. The task of measuring biometric and sanitary indicators of plants during their inventory is set to determine the amount and cost of individual ecosystem services (reducing the volume of pollutants, carbon uptake and sequestration, oxygen production, and regulation of surface water runoff), determining the replacement cost of plants, analysing and interpreting the information obtained, and determining the advantages and disadvantages of this process.

The scientific originality of the study is the first analysis for Ukraine of the possibility and prospects of integrating advanced international tools for evaluating ecosystem services of green spaces in the process of their inventory.

Literature Review

A characteristic feature of the development of the economy of states that pay considerable attention to the implementation of the principles of sustainable development is a substantial change in the approach to financing environmental protection measures. One of the most advanced approaches in this area can be considered the introduction of special payments for the use of services created by ecosystems. This approach to financing eco-balanced development, according to C. Sattler *et al.* (2013), is defined by different terminology but corresponds to the same content subject, and is usually generalised under the brand name PES (Payments for Environmental Services). The concept of PES has recently attracted considerable international interest (Sattler *et al.*, 2013; Schomers *et al.*, 2021; Croci *et al.*, 2022). Ultimately, this approach is considered a very effective economic means of improving environmental management due to the possibility of introducing financial incentives for measures aimed at improving ecosystem services, including those provided by green spaces. According to H. Yan *et al.* (2022), a separate prospect of such financial incentives is the possibility of justifying the feasibility of allocating funds for environmental protection measures based on economic calculations of ecosystem benefits that the state receives from nature (in this case, trees and shrubs).

Awareness of the important role of green spaces in creating a comfortable and safe living space for residents of settlements encourages the development of regular measures for careful treatment, protection, high-quality reproduction, and increasing the area of vegetation in urban landscapes. This direction, in terms of the importance of improving the quality of green spaces while simultaneously meeting the public's demand for environmental services, is also effectively consistent with the requirements of the current legislation in Ukraine. Thus, Law of

Ukraine No. 2059-VIII "On Environmental Impact Assessment" (2017) defines that activities and objects that have or may have a substantial impact on the environment should be analysed in relation to their impact on the environment.

However, green spaces, which have one of the greatest impacts on urban landscapes, as of 2023 do not have a well-defined methodology for assessing their value and the amount of the ecosystem functions they create. For this reason, quite often, when withdrawing green areas for construction, only the cost of a land plot is taken into account without considering an important indicator of assessing the utilities created by green spaces that grew in this territory (Derkulsky, 2016). In this context, there are separate findings regarding the assessment of certain components of the cost of green spaces and the services they perform, according to which researchers use various well-known approaches based on:

- the cost of restoring plantings to the state of their functional purpose (Rogovsky, 2016) using the recommendations of the methodology for determining the replacement cost of green spaces;
- the cost of compensatory landscaping for the purpose of restoring green spaces to replace destroyed or damaged ones (Draft Law ..., 2015);
- accounting for tangible and intangible benefits produced by green spaces (Pryshchepa, 2019; Velasco-Muñoz *et al.*, 2022);
- application of payments for ecosystem services provided, which are created by green spaces in the course of their life (Yan *et al.*, 2022; Gaglio *et al.*, 2023);
- use of information systems, computer modelling, and other tools to automate the determination of the amount and cost of ecosystem services for plantings or individual plants (Nowak *et al.*, 2018; Babí Almenar *et al.*, 2023).

Some Ukrainian researchers are also developing new methods and means for combining the above approaches to consider the advantages and features of each of the methods mentioned (Rogovskiy, 2016; Bidolakh & Lakyda, 2019; Havrylenko & Tsyhanok, 2019). The presence of different approaches and the lack of a unified methodology for estimating the cost of green spaces, the quantitative and monetised expression of their services in Ukraine indicates the need to continue searching for an effective, accessible, and recognised international scientific community methodology for solving this issue.

One of the areas that has international recognition, which is confirmed by a fairly substantial number of publications in the international literature (Nowak *et al.*, 2018; Lin *et al.*, 2020; Mosyaftiani *et al.*, 2022) is the application of the i-Tree Eco special tool for the need to determine individual ecosystem services of trees and shrubs and their replacement cost. However, this approach is poorly tested in Ukraine and requires a more detailed study of its effectiveness, suitability for adaptation to the conditions of the state, and the possibility of integration into the national methodology for the inventory of green spaces.

Materials and Methods

As an experimental base of the study, green spaces of the prefix part of Rayivskyy landscape park were used, which is located near the city of Berezhany, Ternopil region. The geographical location of the experimental base of the study, which covers an area of 1.71 hectares, is described by the following geographical coordinates: north latitude in the range from 49.427485° to 49.428758° and east longitude from 24.938052° to 24.907597°. The height of plant placement above sea level ranges from 322.7 to 339.6 m. In total, the inventory at this facility covers 109 trees.

For trees and shrubs of the attached part of the park, an inventory was conducted during the growing season (July-August 2022) in accordance with the Order of the State Committee for Construction, Architecture and Housing Policy of Ukraine No. 134 "On the Approval of the Instructions on the Inventory of Green Spaces in Populated Areas of Ukraine" (2014). During the implementation of the recommendations of this instruction, additional measurements of plant parameters that are necessary to determine their ecosystem services in accordance with the recommendations of the USDA Forest Service (2021) were simultaneously conducted to evaluate them using the i-Tree Eco toolkit. These parameters include: geographical coordinates of the location of each tree; land use category from a list of 12; the height of the tree from the soil surface to the base of the crown and from this border to the top of the plant; the width of the crown projection in two directions; the proportion of the lost and dead part of the crown (percentage value), and the light exposure of the plant in five categories. The following methods and tools were used to conduct the above-mentioned studies.

Types of woody and shrubby plants were determined by the determinant under the authorship of D.N. Dobrochaeva & Yu.N. Prokudin (1999). The eye estimation of the tree age by morphological features was conducted. Tree diameters were measured with a measuring fork in two mutually perpendicular directions at a height of 1.3 m (Diameter at breast height – DBH), and a measuring tape was used for individual trees of large diameter and with a complex trunk circumference configuration. An Anuchin altimeter was used to measure the height of trees. The geographical longitude and latitude were determined using Garmin GPSMap64s receivers (USA). The USDA Forest Service (2021) guidelines were used to determine the land use category, the proportion of lost and dead crown parts and plant light exposure in five categories. The width of the crown projection was measured with a measuring tape in two mutually perpendicular directions (north-south; west-east).

A flyby was conducted with photographing the territory using a DJI Phantom4 quadcopter (China) to obtain an orthophotoplane in accordance with the methodology (Bidolakh & Lakyda, 2019) using the Agisoft PhotoScan programme for orthotransformation of images and mounting the cartographic basis to obtain an up-to-date cartographic basis. This approach allowed for refining and adjusting the locations of plants obtained from GPS receivers in GIS QGIS 3.16 in accordance with the methodology (Bidolakh & Lakyda, 2019), which, in turn, created conditions for improving the accuracy of the obtained geolocation data of park trees.

Upon completion of the field work to collect the above data, the information processed in accordance with the recommendations of the USDA Forest Service (2021) and interpreted was entered into the i-Tree Eco software. This programme is an adaptation model of Urban Forest Effects, which was developed jointly by individual programmes, public and private companies under the coordination of the US Forest Service.

After processing the data entered in I-Tree Eco tools, information was obtained on the results of evaluating individual ecosystem services (reducing pollutants, carbon uptake and sequestration, oxygen production, and avoided surface runoff) and the replacement cost for both plantings in general and for each tree in particular, in quantitative, qualitative, and cost terms in the form of reports, diagrams, and tables. In addition, I-Tree Eco tools allow exporting geographic information databases in commonly used formats .CSV or .KML, which opens up the possibility of further use of this information for the creation of electronic maps of ecosystem planting services. This feature was used to visualise the results obtained by exporting the geographic information database to the MyMaps (2023) application and presenting it as an interactive plant map (MyMaps…, 2023). This map is publicly available and can be used by all interested parties to obtain information about the ecosystem services of each individual plant.

Results

According to the results of the survey, it was identified that the examined phytolandscapes are represented by 15 tree species, among which the most numerous are *Thuja occidentalis* L. (22.0% of the total population); *Larix decidua* Mill. (19.3%), and *Betula pendula* Roth. (15,6%). The listed species together make up more than half of the plant in terms of quantity, and the remaining tree species are represented in the plantings by a share of no more than 8 per cent. Therewith, it should be noted the presence of individual specimens of large-sised plants, which, even with a small number in the composition of plantings, have a substantial impact on the functioning of the local ecosystem due to their biometric indicators (Table 1).

Table 1. Summary information about plant specimens with the highest biometric indicators

ID	Botanical name	Latitude, degrees	Longitude, degrees	Elevation, m	Landuse	DBH, cm	Crown Dieback, %	Height, m	Base height, m	Top height, m	Crown (NS), m	Crown (EW), m	Missing crown, %	Light exposure, category
18	*Populus Tremula*	49.428263	24.907438	338.3	park	143	38	37.2	6.5	30.7	15.3	17.3	48	3
16	*Fagus sylvatica*	49.428355	24.907541	337.6	park	121	28	37.2	3	34	17.6	15.7	18	3
87	*Fraxinus excelsior*	49.427987	24.90735	339.4	park	102	23	24	9	15	14.2	15.5	38	3
89	*Fraxinus excelsior*	49.427894	24.907109	338.9	park	92	43	26	8	18	12.8	14	28	5
76	*Acer negundo*	49.428224	24.906233	332.5	park	60	18	21	7	14	12.5	14.5	28	4

Notes: Light exposure is evaluated in five categories. Number of sides of the tree receiving sunlight from above (maximum of five). Top of tree is counted as one side
Source: compiled by the author

The area of the calculated (according to I-Tree Eco tools) projection cover of plant crowns is 0.5261 ha, which is 30.1% of the total area of the experimental base of the study and corresponds to 3.765 hectares of leaf area. These data allow concluding that under these experimental conditions, the leaf area of a park with an approximate tent closure of 0.3 exceeds the area of such an object by 2.2 times and the area of the projection cover of plant crowns by 7.2 times.

The results of processing the data entered in I-Tree Eco tools for evaluating individual ecosystem services allowed for analysing of the amount of these utilities in both quantitative and monetised terms. In particular, analysing *the ability of green spaces to reduce the amount of harmful substances* in the biosphere, according to researchers D.J. Nowak *et al.* (2018), trees and shrubs can reduce the concentration of gaseous pollutants in the air by absorbing them with their leaves and needles. The experimental data obtained showed the ability of the examined park stands to extract 355.8 kilograms of polluting gaseous substances from the air annually.

The monetised expression of this ecosystem green space service is estimated at the equivalent of UAH 66.08 thousand (€2,457). Notably, the calculations of this ecosystem service consider the current indicators of pollution in the study region and the specific features of local climatic conditions, which allows for increasing the accuracy of the results and adapting them to local conditions.

Analysis of annual dynamics (Fig. 1) and the total annual absorption of harmful gaseous substances by the examined park plantings showed that the highest value of pollutant extraction is characteristic of solid particles with a size of 2.5-10 microns (PM10) and sulfur dioxide (SO_2). This process was quite intense during the months of March and May, which is explained by the increased concentration of pollutants in the air according to local air pollution data and the intensive process of building up leaf biomass. In general, according to I-Tree Eco Tools, it was identified that the examined trees and shrubs are able to reduce air pollution with harmful compounds (ozone O_3, carbon monoxide CO, and nitrogen dioxide NO_2), and particles of substance size less than 2.5 microns (PM2.5) and 2.5-10 microns (PM10) per 355.8 kilograms of air pollution annually, which in monetised terms is 66.08 thousand UAH (2456.5€) annually.

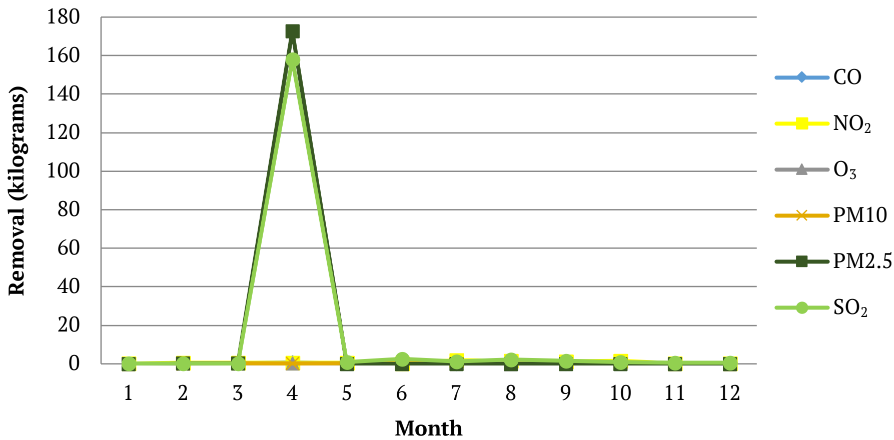

Figure 1. Dynamics of absorption of harmful substances by trees of the attached part of Rayivskyy landscape park

Notes: CO – carbon monoxide; NO_2 – nitrogen dioxide; O_3 – ozone; PM10 – solid particles with a size of 2.5-10 microns; PM2.5 – particles with a substance sise of less than 2.5 microns; SO_2 – sulfur dioxide
Source: compiled by the author

In addition, in 2022, the trees of the attached part of the Rayivskyy landscape park provided the release of about 19.27 kilograms of volatile organic compounds (VOC) (5,881 kilograms of isoprene and 13.39 kg of monoterpenes). This ecosystem function is still difficult to express in a monetised form, but they play an important sanitary and hygienic role due to their ability to destroy and suppress the spread and development of harmful microscopic fungi, pathogenic bacteria, and other forms of negative microorganisms. These compounds are also precursor chemicals for ozone formation. Notably, the release of VOCs into the atmosphere depends on the species composition of the plantation (the number of phytoncidal species) and leaf biomass. According to i-Tree Eco Tools, more than 55% of volatile organic compound emissions are provided by the *Larix decidua* Mill. and *Populus Tremula* L. plants.

Another ecosystem service evaluated in this study was *the properties of green spaces for carbon storage and sequestration*. This function is particularly useful in the context of global climate change when phytolandscapes create conditions to mitigate this change by sequestering carbon from carbon dioxide in their tissues. This property depends on the size and sanitary condition of trees and increases with the growth and development of plants. The gross annual volume of sequestration of trees in the attached part of Rayivskyy landscape park is about 1012 metric tonnes of carbon per year (Fig. 2), with the sssociated cost of 5.59 thousand UAH (€207.8).

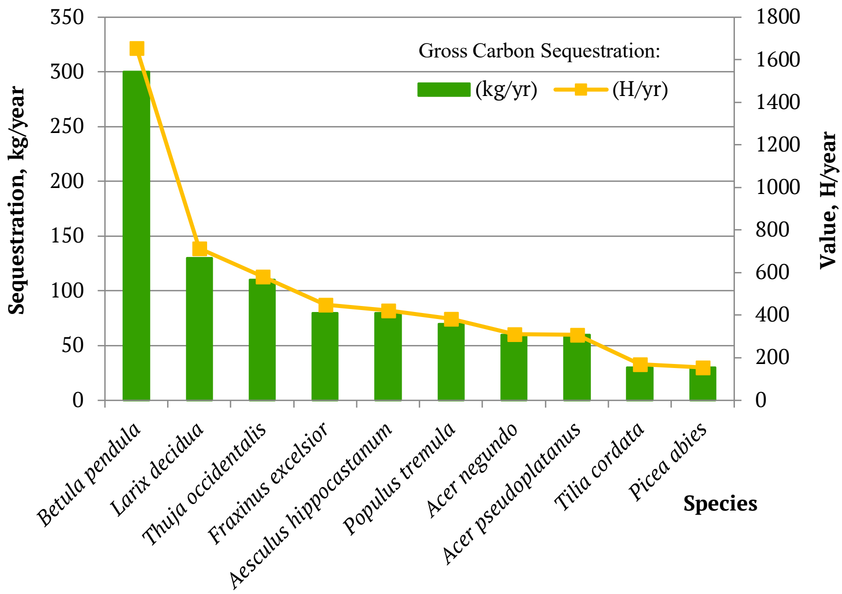

Figure 2. Estimated carbon sequestration and cost of this ecosystem service by main tree species for the attached part of Rayivskyy landscape park

Notes: the sequestration values in the chart are shown in columns, and the cost of ecosystem services is indicated by symbols
Source: compiled by the author

Another part of this ecosystem service for tree stands growing in the adjacent part of Rayivskyy landscape park is the ability to store carbon and its tissues throughout its life cycle. According to I-Tree Eco Tools, the examined plantings are able to store 48.3 metric tonnes of carbon in their tissues (Fig. 3). This ecosystem service is estimated by the programme at 267 thousand hryvnias (€9926). In the context of the experimental base of the study, it was identified that among all species, *Populus Tremula* L. stores the most carbon in its tissues (19.3% of total stored carbon), and *Betula pendula* Roth. is capable of the largest volumes of its sequestration (approximately 29.6% of the total carbon absorbed).

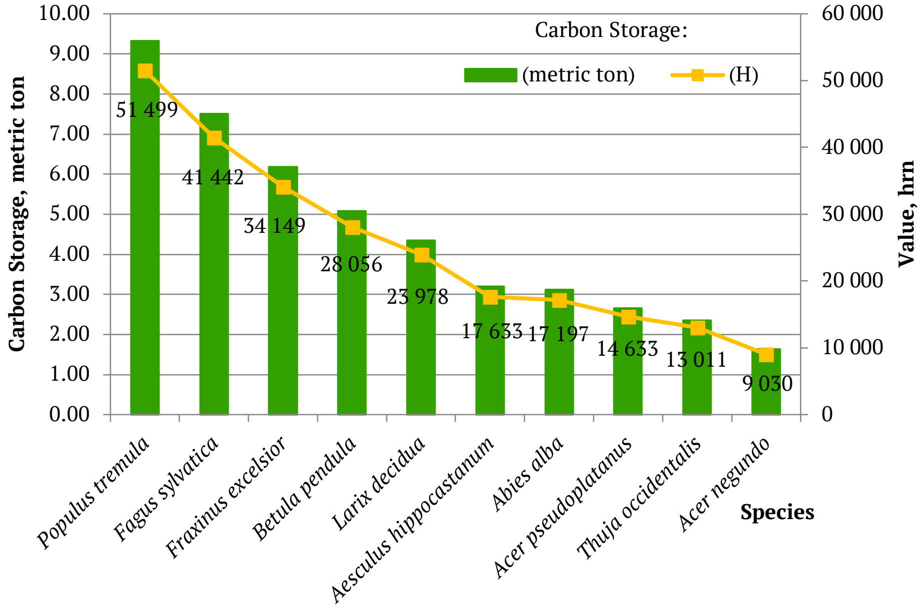

Figure 3. Carbon accumulation in tree tissues and the cost of this ecosystem service in the context of the main tree species for the attached part of Rayivskyy landscape park

Notes: the carbon storage values in the chart are shown in columns, and the cost of ecosystem services is indicated by symbols
Source: compiled by the author

The next important ecosystem service evaluated in this study was *the ability of green spaces to produce oxygen*. Although this service is most often mentioned in the context of useful functions of woody plants, this ecosystem function on a global scale is not so substantial compared to the production of oxygen by aquatic ecosystems (Liqoarobby *et al.*, 2021). However, at the local level, it requires research and evaluation to regulate the oxygen-carbon balance of urban ecosystems. According to i-Tree Eco Tools, the trees of the attached part of Rayivskyy landscape park produce 2,699 metric tonnes of oxygen per year for the plant under study. The highest amount of oxygen production among the trees of the experimental base of the study are achieved by the species prevailing in the park space: *Betula pendula* Roth., *Larix decidua* Mill., and *Thuja occidentalis* L. due to their substantial number (Table 2). Therewith, trees with the highest biometric indicators and a large leaf area are characterised by maximum individual oxygen productivity: *Fraxinus excelsior* L., *Aesculus hippocastanum* L., and *Populus Tremula* L.

Table 2. List of species with the highest oxygen productivity in 2022 (on the territory of the attached part of Rayivskyy landscape park)

No.	Species	Oxygen production, kg	Annual gross carbon uptake, kg	Number of trees	Leaf area, ha
1	*Betula pendula*	799.46	299.80	17	0.63
2	*Larix decidua*	345.09	129.41	21	0.44
3	*Thuja occidentalis*	280.73	105.27	24	0.33

Table 1, Continued

No.	Species	Oxygen production, kg	Annual gross carbon uptake, kg	Number of trees	Leaf area, ha
4	*Fraxinus excelsior*	216.24	81.09	2	0.21
5	*Aesculus hippocastanum*	203.63	76.36	6	0.50
6	*Populus tremula*	185.69	69.64	6	0.44
7	*Acer negundo*	149.77	56.16	2	0.13
8	*Acer pseudoplatanus*	149.39	56.02	3	0.09
9	*Tilia cordata*	81.33	30.50	3	0.09
10	*Abies alba*	74.61	27.98	8	0.09

Source: compiled by the author based on USDA Forest Service (2021)

Another ecosystem service that was evaluated in this paper was *the avoided runoff by green spaces*.

This ecosystem function is quite important for urban landscapes due to the ability of trees to reduce and regulate surface runoff by trapping some of the precipitation with their crowns, creating a mechanical barrier to water movement on the soil surface, and transferring external water movement into intra-soil runoff. Therewith, trees perform important anti-erosion, protective, and water-regulating functions. The study allowed establishing that the trees of the attached part of the Rayivskyy landscape park annually help to avoid about 149 cubic meters of runoff, which is estimated by the i-Tree Eco Tools (Fig. 4) programme in the amount of 10 thousand UAH (€372) annually. These indicators are calculated based on local meteorological data (with annual precipitation of 91.9 centimetres) and biometric parameters of the park's trees.

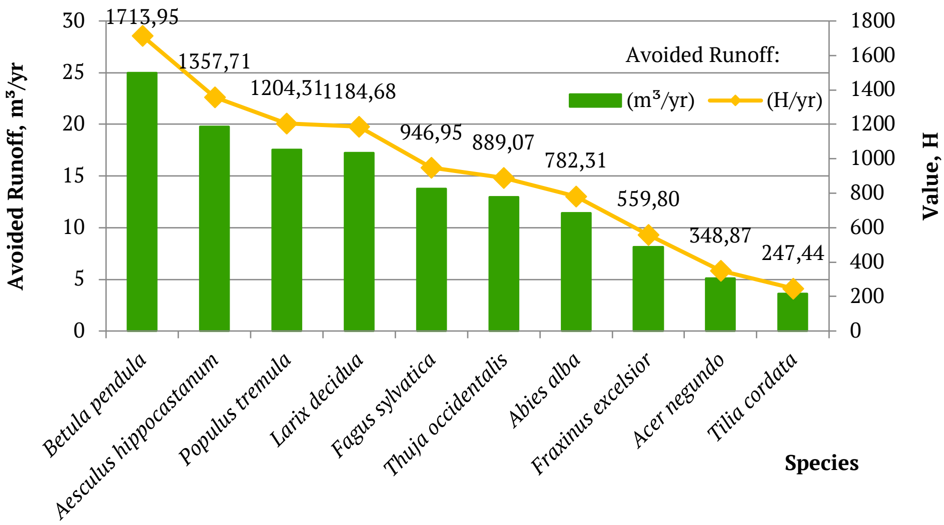

Figure 4. The amount of avoided runoff by tree species of the attached part of Rayivskyy landscape park and the cost of this ecosystem service

Notes: the values of the volume of surface runoff regulation in the chart are shown in columns, and the cost of ecosystem services is indicated by symbols

Source: compiled by the author based on USDA Forest Service (2021)

The replacement cost of green spaces is also an important indicator in the context of assessing the importance of plants for urban landscapes, because, according to the methodology (Order of the Ministry..., 2018), it should provide for the cost of creating and maintaining similar phytolandscapes, considering the characteristics that determine their value. In this case, the USDA Forest Service (2021) methodology has its advantages in the context of considering biometric indicators of plantings, land use category, plant life status and ecosystem value, and local conditions. Therewith, the essence of the approach used in I-Tree Eco Tools is similar, and consists in calculating the potential cost of replacing a plant with a similar one, considering their functional importance. Plantings of the attached part of Rayivskyy landscape park, according to the i-Tree Eco Tool (Fig. 5), are estimated at 4486,464 thousand UAH (€166,783) of the total replacement cost of trees.

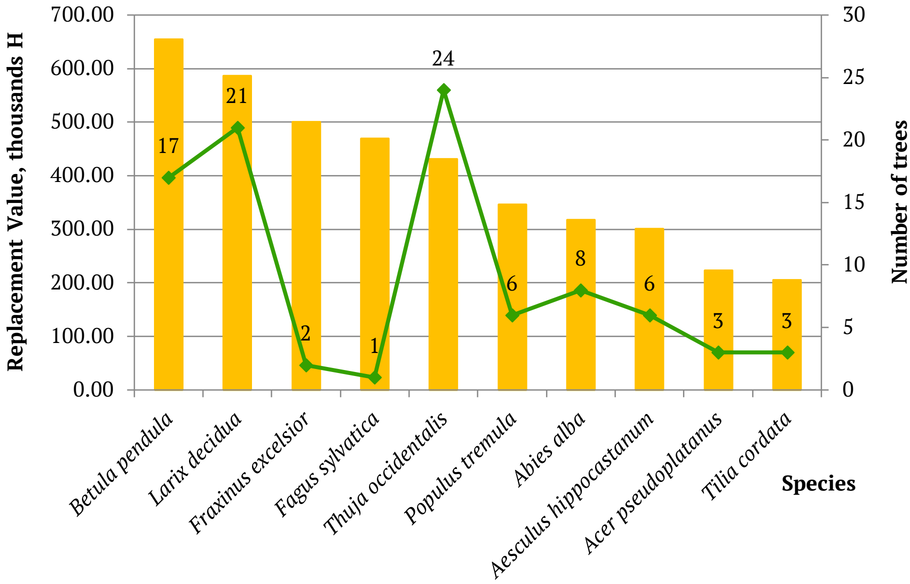

Figure 5. Tree species with the highest replacement cost of the attached part of Rayivskyy landscape park

Notes: the replacement cost values in the chart are shown in columns, and the number of trees of this type is indicated by symbols
Source: compiled by the author based on USDA Forest Service (2021)

Evaluating the entire list of ecosystem services examined in this paper and their replacement cost (Table. 3), the annual cost of the examined ecosystem services (Gross Carbon Sequestration, Avoided Runoff, and Pollution Removal) for the attached part of the Rayivskyy landscape park, in general, is 81894 UAH (€3044). That is, each tree in this park annually produces an average of UAH 751.32 (€27.93) in the context of the examined three ecosystem services. In addition, the park space contains 48.26 carbon atoms in its tissues, which can be estimated at 266,662 thousand UAH (€9913.09). The total replacement cost of the examined plantings is 4486,464 thousand UAH (€166,783).

Table 3. Consolidated volumes and cost of ecosystem services for trees growing on the territory of the attached part of Rayivskyy landscape park

No.	Species	Trees Number	Carbon Storage		Gross Carbon Sequestration		Avoided Runoff		Pollution Removal		Replacement Value, H
			Metric ton	H	Metric ton/yr	H/yr	m^3/yr	H/yr	Metric ton/yr	H/yr	
1	*Abies alba*	8	3.11	17197.36	0.02	133.90	11.39	782.31	0.03	5506.64	317060.27
2	*Acer negundo*	2	1.63	9029.90	0.06	310.34	5.08	348.87	0.01	1835.55	121792.24
3	*Acer pseudoplatanus*	3	2.65	14633.06	0.06	309.54	3.39	232.70	0.01	1835.55	223467.39
4	*Aesculus hippocastanum*	6	3.19	17632.75	0.08	421.95	19.77	1357.71	0.05	9177.74	301295.69
5	*Betula pendula*	17	5.08	28056.28	0.30	1656.57	24.95	1713.95	0.06	11013.29	654105.52
6	*Fagus sylvatica*	1	7.50	41442.15	0.00	1.37	13.79	946.95	0.03	5506.64	469030.21
7	*Fraxinus excelsior*	2	6.18	34148.54	0.08	448.07	8.15	559.80	0.02	3671.10	499858.47
8	*Larix decidua*	21	4.34	23978.28	0.13	715.07	17.25	1184.68	0.04	7342.19	586001.33
9	*Picea abies*	8	1.30	7178.70	0.03	154.60	3.47	238.02	0.01	1835.55	161943.25
10	*Pinus sylvestris*	2	0.19	1053.39	0.02	105.29	2.46	168.80	0.01	1835.55	66331.15
11	*Populus tremula*	6	9.32	51499.26	0.07	384.78	17.53	1204.31	0.04	7342.19	345879.45
12	*Quercus rubra*	2	0.45	2494.73	0.02	94.18	3.19	218.97	0.01	1835.55	79165.71
13	*Sorbus aucuparia*	4	0.08	421.67	0.02	107.74	1.85	127.14	0.00	0.00	24618.18
14	*Thuja occidentalis*	24	2.35	13011.36	0.11	581.70	12.94	889.07	0.03	5506.64	430959.52
15	*Tilia cordata*	3	0.88	4884.74	0.03	168.52	3.60	247.44	0.01	1835.55	204955.71
	Total	109	48.26	266662.18	1.01	5593.64	148.81	10220.73	0.36	66079.73	4486464.11

Notes: Tree species are listed in alphabetical order. Values of Carbon Storage and Replacement values are given for all plants of this species at the time of the study (2022). For ecosystem services Gross Carbon Sequestration, Avoided Runoff, and Pollution Removal are given annual data
Source: compiled by the author

Analysing the tree annual utility, its maximum value is characteristic of *Fagus sylvatica* L. (6455 UAH or €240), *Fraxinus excelsior* L. (2339 UAH or €87), and *Aesculus hippocastanum* L. (1826 UAH or €68). The lowest values of annual utility in the context of the examined indicators are typical for plants with low biometric indicators (*Sorbus aucuparia* L. and *Thuja occidentalis* L.). When assessing the sub-tree ecosystem value in terms of carbon storage and replacement cost, its highest indicator is characteristic of *Fagus sylvatica* L. – 510,472 thousand UAH (€18,977), *Fraxinus excelsior* L. 267,004 UAH (€9,926) and *Acer pseudoplatanus* L. – 79,367 UAH (€2,95).

Discussion

This analysis shows that typical forest and park tree species that can reach substantial sizes can perform the greatest number of ecosystem functions in the context of carbon storage and sequestration, oxygen production, pollution removal, and avoided runoff. The highest rates of replacement cost also characterise them, because it is extremely difficult to replace the ecosystem services of such large-sized trees, especially in a short period of time. This implies the importance of protecting and carefully caring for century-old trees, given their value for urban ecosystems. Other researchers agree with this conclusion (Piovesan *et al.*, 2022), which, by investigating the importance of such plants for ecosystem restoration, identify them as an indispensable resource for preserving the forest and park environment.

However, on the other hand, it is necessary not to underestimate the value of small trees and shrubs, which are characterised by a much smaller feeding area and usually have higher decorative qualities, that is, they perform ecosystem functions of a different nature (decorative, aesthetic, cultural, and educational, etc.). Due to the complexity of cost estimation and quantitative expression, these services are often considered when determining the ecosystem value of plantings, but other researchers are already conducting studies in this direction (Vallecillo *et al.*, 2019). Therefore, green spaces are a rather complex biogeocenosis, in which each element performs its own important ecosystem services and requires proper attention and research.

In the course of the study, the feasibility of using one of the tools for assessing the cost of ecosystem functions of i-Tree Eco green spaces in the course of their inventory was tested on the example of the attached part of Rayivskyy landscape park. Based on the results of the study, it was established that the USDA Forest Service (2021) methodology is capable of integration not only into the US green space accounting system, but also into the methods of inventory of plantings in other countries (Raum *et al.*, 2019; Cimburova & Barton, 2020; Gong *et al.*, 2022), including, based on the results of this study, and in the national methodology for inventory of green spaces (Order of..., 2014) by measuring a number of additional biometric indicators of plants. This approach, even if the typical process of performing an inventory of trees and shrubs is slow and complicated, opens up new opportunities for obtaining important information about the ecosystem functions of plantings and the replacement cost of each plant.

When evaluating the possibility of adapting i-Tree Eco tools to local conditions, it is necessary to note that this toolkit uses a number of input national (current exchange rate and cost of basic energy resources) and local parameters (information on sources, volumes, and dynamics of pollution; information from the nearest meteorological stations on climate data of the region; the number of inhabitants of the locality, etc.). This approach creates conditions for assessing the quantitative and cost parameters of ecosystem services and adapting them to local climatic and economic conditions, considering other specific features of the territory for which the study is performed.

The disadvantages of the proposed approach include the need to enter information about the contamination of the study region in a special form and the need to perform additional measurements, which increases the complexity and duration of the examination. Therewith, the advantage of using i-Tree Eco tools when conducting an inventory of green spaces is the substantial volume, informative content and value of materials, various forms of presentation of results and new opportunities for further use. In particular, the possibility of automated preparation of reports, tabular, and graphic material for each plant, and for the species range, or for planting creates conditions for simplifying and improving the quality of further interpretation of the information received. The ability to obtain data on the implementation of ecosystem services in quantitative and monetised terms increases the information content of research results not only for researchers but also for territorial communities, state authorities, public organisations, and residents of localities. This approach, considering the existing experience of other researchers (Ly & Xiao, 2016; Raum *et al.*, 2019; Almenar *et al.*, 2023), should also improve the quality and validity of decision-making in the country regarding the importance of protecting green spaces and performing regular care for them, the feasibility of replacing individual plants in plantings that cease to perform their ecosystem functions and the list of species that should be used in this case.

Under such conditions, an important area of use of the information obtained in this way is to bring it to a wide range of users. In this direction, according to the studies (Rocha *et al.*, 2015; Bidolakh, 2020; Mosyaftiani *et al.*, 2022), visualisation of tree ecosystem services using interactive maps and mapping useful functions of plantings are effective. The use of the Google Mymaps (2023) application, in accordance with the above methodology, created conditions for communicating information about the ecosystem services of each park tree to each interested person in the form of an electronic map (Fig. 6).

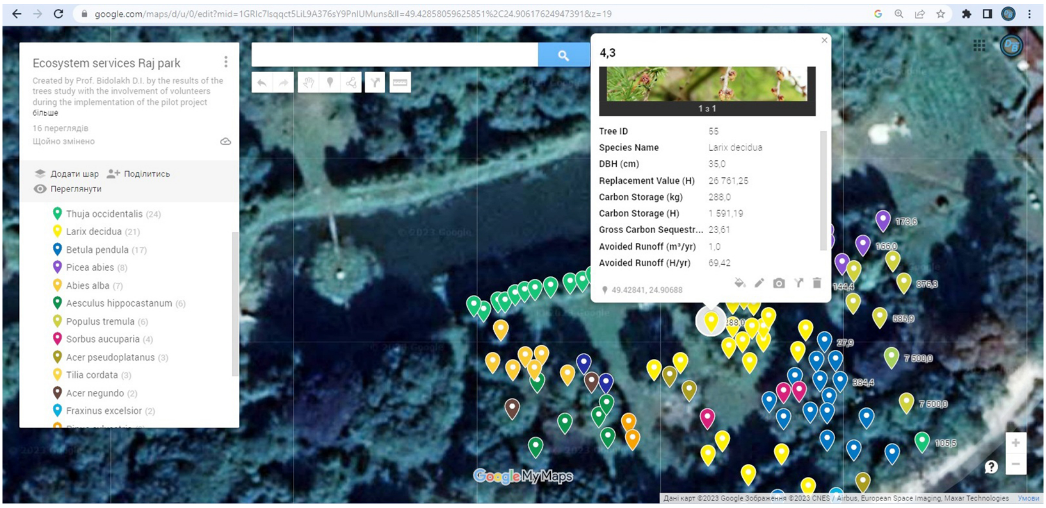

Figure 6. Interactive map of the number and cost of ecosystem services of green spaces on the territory of the attached part of Rayivskyy landscape park, Ternopil region

Source: developed by the author based on USDA Forest Service (2021), Mymaps Google (2023)

In addition, everyone who can be present in Rayivskyy landscape park has the opportunity to work with this application on their smartphone or other gadgets in interactive mode. If geolocation is enabled, the user can get information directly about each tree while being near it. The proposed approach, provided that it is used for other objects of improvement, will also increase the information content of residents of these settlements regarding the useful functions of each individual tree or bush for the urban environment, awareness of the value of green spaces, and increase ecological consciousness. In this context, the general trend of increasing the number of studies and publications towards the need to ecologise social development is notable (Yang & Khan, 2021; Gaglio *et al.*, 2023; Stoeckl *et al.*, 2023). The researchers agree that the ongoing processes of economic growth, technological development, and urbanisation degrade the ecosystem sustainability of the environment and require the introduction of mechanisms and policies that, on the contrary, will contribute to raising the level of environmental awareness of the population. Under such conditions, the presented results of the study can not only increase the information content of the results of the inventory of green spaces but also contribute to the process of greening social development in Ukraine.

Conclusions

The study allowed demonstrating the importance of assessing the ecosystem functions of green spaces when performing their inventory to ensure sustainable ecosystem development. One of the most promising tools in this regard is i-Tree Eco, which allows obtaining, interpreting, and further presenting information about the ecological and cost value of green spaces. The approbation performed in this study on the integration of this toolkit into the process of interpreting the results of measuring biometric and sanitary indicators of plants based on the results of their inventory showed the possibility and feasibility of such an approach, considering the value of the information received. The use of i-Tree Eco tools in this direction allows for determining the amount and cost of individual ecosystem services (Polution removal, carbon storage and sequestration, oxygen production, and avoided runoff), evaluating the replacement cost of plants, analysing, and interpreting the information obtained. This approach improves the quality and validity of decision-making in the protection and use of natural resources.

The disadvantages of this process include the need to perform additional measurements, increase the complexity and duration of the examination. A substantial advantage of using i-Tree Eco tools during inventory management is the substantial volume, informative content, the value of materials, and various forms of presentation and interpretation of results. Creating interactive maps of the ecosystem utility of each tree to visualise information for a wide range of users is proposed, which will increase the ecological consciousness of residents.

The study also allowed establishing the annual cost of ecosystem utilities (in the context of the examined ones) for the attached part of Rayivskyy landscape park in the amount of 81894 UAH (€3044) and the total replacement cost of the examined plantings in the amount of 4486,464 thousand UAH (€166,783). Notably, species that can reach substantial sizes can perform the greatest number of ecosystem functions in the context of the examined indicators. Accordingly, they are characterised by the highest rates of replacement cost, which indicates the importance of their care and protection.

It should also be noted the importance of further research on the possibilities of attracting new tools and expanding the list of ecosystem benefits that will be examined during the inventory of green spaces.

Conflict of Interest

The author declares no conflict of interest.

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References

[1] Babí Almenar, J., Petucco, C., Sonnemann, G., Geneletti, D., Elliot, T., & Rugani, B. (2023). Modelling the net environmental and economic impacts of urban nature-based solutions by combining ecosystem services, system dynamics and life cycle thinking: An application to urban forests. *Ecosystem Services*, 60, article number 101506. doi: 10.1016/j.ecoser.2022.101506.

[2] Bidolakh, D.I. (2020). Geoinformation monitoring of green stands using remote sensing methods. *Ukrainian Journal of Forest and Wood Science*, 11(2), 4-14. doi: 10.31548/forest2020.02.004.

[3] Bidolakh, D.I., & Lakyda, P.I. (2019). Inventory of green plants using modern information technologies. *Forestry and Landscape Gardening*, 16, 126-132.

[4] Chan, C.-S., Si, F.H., & Marafa, L.M. (2018). Indicator development for sustainable urban park management in Hong Kong. *Urban Forestry & Urban Greening*, 31, 1-14. doi: 10.1016/j.ufug.2018.01.025.

[5] Cimburova, Z., & Barton, D.N. (2020). The potential of geospatial analysis and Bayesian networks to enable i-Tree Eco assessment of existing tree inventories. *Urban Forestry & Urban Greening*, 55, article number 126801. doi: 10.1016/j.ufug.2020.126801.

[6] Croci, E., Lucchitta, B., & Penati, T. (2022). An urban PES model for diffused green areas requalification and maintenance in Milan. *Environmental Science & Policy*, 130, 47-60. doi: 10.1016/j.envsci.2022.01.018.

[7] Derkulsky, R.Yu. (2016). Problems of degradation of recreational and nature conservation areas of Kyiv sity and assessment of biodiversity loss in the context of future integration into the EU NATURA 2000 ecological network. *Land Management, Cadastre and Land Monitoring*, 1/2, 146-157.

[8] Dobrochaeva, D.N., & Prokudin, Yu.N. (Eds.). (1999). *Determinant of higher plants for Ukraine*. Kiev: Fitosotsiotsentr.

[9] Draft Law No. 2013a. "On Green Areas of Cities and Other Settlements". (2015, June). Retrieved from https://w1.c1.rada.gov.ua/pls/zweb2/webproc4_1?pf3511=55455.

[10] Gaglio, M., Lanzoni, M., Goggi, F., Fano, E.A., & Castaldelli, G. (2023). Integrating payment for ecosystem services in protected areas governance: The case of the Po Delta Park. *Ecosystem Services*, 60, article number 101516. doi: 10.1016/j.ecoser.2023.101516.

[11] Gong, C., Xian, C., & Ouyang, Z. (2022). Assessment of NO2 purification by urban forests based on the i-Tree eco model: Case study in Beijing, China. *Forests*, 13(3), article number 369. doi: 10.3390/f13030369.

[12] Havrylenko, O., & Tsyhanok, E. (2019). Degradation of ecosystem services of protected areas in urbanized zones. *Bulletin of Taras Shevchenko National University of Kyiv. Geography*, 73, 10-14. doi: 10.17721/1728-2721.2019.73.2.

[13] Law of Ukraine No. 2059-VIII "On Environmental Impact Assessment". (2017, May). Retrieved from https://zakon.rada.gov.ua/laws/show/2059-19#Text.

[14] Lin, J., Kroll, C., & Nowak, D. (2020). Ecosystem service-based sensitivity analyses of i-Tree Eco. *Arboriculture & Urban Forestry*, 46(4), 287-306. doi: 10.48044/jauf.2020.021.

[15] Liqoarobby, R., Sunardi, Suparman, Y., & Fadilah, K. (2021). Aqueous systems of dissolved oxygen in reservoir. *E3S Web of Conferences*, 249, article number 03015. doi: 10.1051/e3sconf/202124903015.

[16] Ly, T.P., & Xiao, H. (2016). The choice of a park management model: A case study of Phong Nha-Ke Bang National Park in Vietnam. *Tourism Management Perspectives*, 17, 1-15. doi: 10.1016/j.tmp.2015.10.004.

[17] Melnyk, Y.A., Hrynyk, H.H., & Hrynyk, O.M. (2019). Results of the inventory of dendropark "Podillya" of Khmelnitsky city. *Scientific Bulletin of UNFU*, 29(7), 101-107. doi: 10.15421/40290720.

[18] Mosyaftiani, A., Wahyu, A., Kaswanto, K., Wiyoga, H., Syasita, N., Septa, A.F., & Djauhari, D. (2022). Monitoring and analyzing tree diversity using i-Tree eco to strengthen urban forest management. *Biodiversitas Journal of Biological Diversity,* 23(8), 4033-4039. doi: 10.13057/biodiv/d230822.

[19] Mymaps Google. (2023). *Mymaps ecosystem services Raj park, Berezhany.* Retrieved from https://www.google.com/maps/d/u/0/edit?mid=1GRIc7lsqqct5LiL9A376sY9PnIUMuns&usp=sharing.

[20] Nowak, D.J., Hirabayashi, S., Doyle, M., McGovern, M., & Pasher, J. (2018). Air pollution removal by urban forests in Canada and its effect on air quality and human health. *Urban Forestry & Urban Greening*, 29, 40-48. doi: 10.1016/j.ufug.2017.10.019.

[21] Order of State Committee for Construction, Architecture and Housing Policy of Ukraine No. 134 "On the Approval of the Instructions on the Inventory of Green Spaces in Populated Areas of Ukraine". (2014, May). Retrieved from https://zakon.rada.gov.ua/laws/show/z0182-02?lang=en#Text.

[22] Order of the Ministry of Housing and Utilities of Ukraine No. 210 "On the Approval of the Methodology for Determining the Replacement Value of Green Spaces". (2018, August). Retrieved from https://zakon.rada.gov.ua/laws/show/z0549-09#Text.

[23] Piovesan, G., Cannon, C.H., Liu, J., & Munné-Bosch, S. (2022). Ancient trees: irreplaceable conservation resource for ecosystem restoration. *Trends in Ecology & Evolution,* 37(12), 1025-1028. doi: 10.1016/j.tree.2022.09.003.

[24] Pryshchepa, A.M. (2019). Ecosystem services of urbosystems green plantations. *Scientific Reports of NULES of Ukraine*, 77(1), 1-12. doi: 10.31548/dopovidi2019.01.004.

[25] Raum, S., Hand, K.L., Hall, C., Edwards, D.M., O'Brien, L., & Doick, K.J. (2019). Achieving impact from ecosystem assessment and valuation of urban greenspace: The case of i-Tree Eco in Great Britain. *Landscape and Urban Planning*, 190, article number 103590. doi: 10.1016/j.landurbplan.2019.103590.

[26] Rocha, S.M., Zulian, G., Maes, J., & Thijssen, M. (2015). *Mapping and assessment of urban ecosystems and their services*. Brussels: Joint Research Centre. doi: 10.2788/638737.

[27] Rogovskiy, S.V. (2016). Method of determining trees replacement cost in settlements green areas. *Scientific Bulletin of UNFU*, 26(4), 45-52. doi: 10.15421/40260407.

[28] Rohovskyi, S.V., Oleschko, O.G., Jychareva, K.V., Strunynska, J.V., & Kolotnicka, O.V. (2021). Current problems of plant inventory in urban plantations and experience in their solution. *Scientific Bulletin of UNFU*, 31(5), 60-66. doi: 10.36930/40310509.

[29] Sattler, C., Trampnau, S., Schomers, S., Meyer, C., & Matzdorf, B. (2013). Multi-classification of payments for ecosystem services: How do classification characteristics relate to overall PES success? *Ecosystem Services*, 6, 31-45. doi: 10.1016/j.ecoser.2013.09.007.

[30] Schomers, S., Meyer, C., Matzdorf, B., & Sattler, C. (2021). Facilitation of public payments for ecosystem services through local intermediaries: An institutional analysis of agri-environmental measure implementation in Germany. *Environmental Policy and Governance*, 31(5), 520-532. doi: 10.1002/eet.1950.

[31] Steenberg, J.W.N., Millward, A.A., Nowak, D.J., & Robinson, P.J. (2017). A conceptual framework of urban forest ecosystem vulnerability. *Environmental Reviews*, 25(1), 115-126. doi: 10.1139/er-2016-0022.

[32] Stoeckl, N., Dodd, A., & Kompas, T. (2023). The monetary value of 16 services protected by the Australian National Biosecurity System: Spatially explicit estimates and vulnerability to incursions. *Ecosystem Services*, 60, article number 101509. doi: 10.1016/j.ecoser.2023.101509.

[33] *USDA Forest Service. (2021). i-Tree Eco Users Manual (version 6.0).* Retrieved from https://www.itreetools.org/documents/275/EcoV6_UsersManual.2021.09.22.pdf.

[34] Vallecillo, S., La Notte, A., Zulian, G., Ferrini, S., & Maes, J. (2019). Ecosystem services accounts: Valuing the actual flow of nature-based recreation from ecosystems to people. *Ecological Modelling*, 392, 196-211. doi: 10.1016/j.ecolmodel.2018.09.023.

[35] Velasco-Muñoz, J.F., Aznar-Sánchez, J.A., Schoenemann, M., & López-Felices, B. (2022). An analysis of the worldwide research on the socio-cultural valuation of forest ecosystem services. *Sustainability*, 14(4), article number 2089. doi: 10.3390/su14042089.

[36] Yan, H., Yang, H., Guo, X., Zhao, S., & Jiang, Q. (2022). Payments for ecosystem services as an essential approach to improving ecosystem services: A review. *Ecological Economics*, 201, article number 107591. doi: 10.1016/j.ecolecon.2022.107591.

[37] Yang, X., & Khan, I. (2021). Dynamics among economic growth, urbanization, and environmental sustainability in IEA countries: The role of industry value-added. *Environmental Science and Pollution Research*, 29, 4116-4127. doi: 10.1007/s11356-021-16000-z.

Оцінка екосистемних функцій зелених насаджень, як важлива складова їх інвентаризації у контексті сталого розвитку урболандшафтів

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Анотація. Важливим напрямком досліджень у контексті забезпечення сталого розвитку урбоекосистем є опрацювання теоретичних та прикладних аспектів можливостей одержання інформації про екосистемну корисність зелених насаджень. Концепція оцінювання та оплати екопослуг, які продукують дерева та кущі для довкілля та суспільства характеризується значним міжнародним інтересом. У цьому контексті важливим є аналіз сучасного інструментарію та методик, які здатні адекватно визначати та оцінювати обсяги екосистемних послуг, що і стало головною метою дослідження. У цій роботі проведено апробацію можливості залучення інструментарію i-Tree Eco для кількісного та вартісного визначення обсягів створюваних парковими насадженнями екосистемних послуг до процесу інвентаризації зелених насаджень. Для цього, на прикладі приставкової частини Раївського парку Тернопільської області, проведено вимірювання біометричних та санітарних показників дерев під час їх інвентаризації, визначено ряд екосистемних послуг рослин (зменшення обсягів забруднюючих речовин, поглинання та секвестрація вуглецю, продукування кисню та регулювання поверхневого водного стоку), встановлено відновну вартість дерев, проаналізовано отримані дані, виконано інтерпретацію отриманої інформації у вигляді інтерактивної електронної карти а також визначено переваги і недоліки цього процесу. Проведене дослідження засвідчило, що вартість екосистемних послуг (у розрізі досліджених показників) для приставкової частини Раївського парку складає 81894 грн (€3044) на рік, а загальну відновну вартість дослідженого насадження становить 4486,464 тис. грн. (€166,783). Монетизований вираз екосистемної корисності цього насадження створює умови для покращення розуміння цінності фітоценозу для урболандшафтів. Практичною цінністю дослідження є можливість використання результатів для удосконалення та підвищення інформативності процесу інвентаризації зелених насаджень, шляхом одержання інформації про екосистемні послуги дерев у кількісному та вартісному виразі з метою підвищення обґрунтованості рішень у сфері природокористування

Ключові слова: монетизація корисності; відновна вартість дерев та кущів; i-Tree Eco; оздоровлення довкілля; вікові дерева

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Results of experimental studies on the strength of adhesive-bonded joints of thermally modified ash wood

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Abstract. It is necessary to ensure the protection of the adhesive-bonded wood structures from the effects of temperature and humidity loads to improve their performance characteristics and increase the service life – this determines the relevance of this study. The purpose of the study is to examine, using a long-term method, the strength of thermoplastic adhesive-bonded joints of thermally modified ash wood and unmodified pine wood. The data were subjected to statistical processing and analysis. The experimental samples for the studies were prepared according to the proposed methodology in production conditions according to the existing technological process. The studies continued for two years, with periodic inspection of the samples and recording of the changes that occurred during the experiments. Regularly, every three months of the study, part of the samples was removed from the stand and tested to determine the change in strength. Methods were selected and described for conducting long-term experimental studies to determine the strength of adhesive joints of thermally modified ash wood and unmodified pine wood glued with polyvinyl acetate-based adhesives with durability class D4. Based on the study results, it was identified that the average strength of control samples of the thermally modified ash wood and unmodified pine wood was 7.12 MPa, and after two years of long-term testing, it decreased to 5.13 MPa (27.9%). In addition, it was identified that the operation of such adhesive-bonded joints in natural conditions depends on the cyclic temperature-and-humidity load. Namely, in

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the summer-autumn period, the strength decreases, while in the winter-spring period, it remains unchanged, and in some cases, increases. The obtained results are of great practical importance, since such adhesive-bonded structures, can be used for the manufacture of joinery and building products, which will improve their performance characteristics and increase their service life

Keywords: long-term method; pine; atmospheric factors; temperature-and-humidity loads; service life; adhesion

Introduction

Wood is an anisotropic, fibrous structural material that has certain advantages over other materials. L Kristak *et al*. (2021), Y. Li *et al*. (2021), R. Afshar (2022) described that there are also disadvantages that limit its use in conditions with variable temperature and humidity loads. To eliminate these shortcomings and for rational use of wood, it is subject to modification (especially low-value and low-grade varieties). In the studies by Sandberg *et al.* (2017), D. Jones & D. Sandberg (2020), Repič *et al.* (2022), several methods of wood modification were examined, one of which is thermal modification. As a result of this modification, physical and mechanical properties of the wood change, including increased resistance to variable humidity and temperature conditions of operation compared to unmodified wood (Heat treatment…, 2017; Hill *et al*., 2021; Giridhar & Pandey; 2022).

Therewith, there is a problem with gluing such wood because during the modification process, exposure to high temperatures changes the chemical composition, physical and mechanical properties of wood, including its adhesive properties (Candelier *et al*., 2017; Kozakiewicz *et al*., 2020; Zigon *et al*., 2020). To date, several studies were conducted (Biazzon *et al.,* 2019; Chang *et al.,* 2019) regarding the bonding of thermally modified wood together. However, there are no studies on the bonding of thermally modified wood with unmodified wood. This problem cannot be solved without thorough research in this area.

P. Král *et al.* (2015) note that for bonding thermally modified and unmodified wood together, both thermosetting (phenol-formaldehyde, urea-formaldehyde, polyurethane, etc.) adhesives and thermoplastic adhesives (polyvinyl acetate) are used. Thermosetting adhesives better withstand variable humidity and temperature loads of the environment, cure quickly, form a mesh structure of the adhesive joint, and are relatively inexpensive.This ensures proper water, humidity, and heat resistance of the adhesive joints. However, they are environmentally dangerous both in the process of preparing glue and during the operation of finished products. In addition, such adhesives have a high percentage of moisture absorption and low adhesive properties to thermally modified wood, which does not allow the adhesive joints to provide proper strength under operating conditions. Kshyvetskyy *et al.* (2019) state that modern thermoplastic (polyvinyl acetate) adhesives have good adhesive properties to wood, provide proper strength of adhesive joints, and are eco-friendly and easy to use, which makes them promising for use.

To solve these problems, the authors decided to conduct experimental studies to examine the adhesive strength of adhesive-bonded joints of thermally modified ash wood and unmodified pine wood glued with thermoplastic polyvinyl acetate adhesives with durability class D4 (Datskiv & Kshyvetskyy, 2020).

The purpose of the study was investigating changes in the strength of thermoplastic adhesive joints of thermally modified ash wood and unmodified pine wood by the long-term method.

The object of the study is adhesive joints of thermally modified ash wood and unmodified pine wood. The subject of the study is the strength of thermally modified ash wood and unmodified pine wood glued together with thermoplastic adhesives.

The following tasks were set to achieve this goal:

1. Describe the method of conducting long-term experimental studies on the strength of adhesive joints of thermally modified ash wood with unmodified pine wood.

2. Conduct experimental studies to determine the strength of adhesive joints of thermally modified ash wood and unmodified pine wood by applying the long-term method.

3. Analyse the obtained results on changes in the strength of adhesive joints of thermally modified ash wood and unmodified pine wood.

Bonding of thermally modified wood and unmodified wood is promising for the joinery and construction industry, mainly in the manufacture of window blocks, since there is a problem with their durability during operation, especially outdoor operating conditions. Modern paint and varnish materials are not able to provide proper operating conditions for windows with prolonged negative effects of external factors. This problem can be solved by using an adhesively-bonded structure that combines thermally modified wood and unmodified wood.

Materials and Methods

The experimental studies determining the strength of adhesive-bonded joints of thermally modified ash wood and unmodified pine wood were conducted in accordance with the requirements of tests in natural conditions (from November 7, 2019, to November 7, 2021), and the samples were prepared in accordance with the DSTU EN 205:2014 standard (2014). For bonding, a thermoplastic adhesive based on polyvinyl acetate RAKOLL ECO 4 (Germany) with durability class D4 was used.

The formation of adhesive joints was conducted on the basis of the Long Life Wood enterprise (Kyiv, Ukraine) under production conditions using the existing technological equipments. Thermal modification of ash wood was conducted in an autoclave for 12 hours at a temperature of 195°C. After the thermal modification, the samples were conditioned (18 hours).

The first stage was the manufacture of blanks (lamela), the dimensions of which were 600x130x5 mm. They were calibrated to a thickness of 5±0.1 mm before bonding. The moisture content of pine wood slats was 12±1.5% and that of thermally modified ash wood – 6±0.5%. A laboratory moisture analyser RAD WAG WPS 110 S (Poland) was used to determine the moisture content of the workpieces. The glue was applied manually with a brush. The adhesive was thoroughly stirred up before application until a homogeneous mass was obtained. The glue consumption was 160 g/m^2. The viscosity was measured using a VZ-4 viscometer and adjusted to the requirements of the bonding mode parameters (70 seconds). After applying the glue, a workpiece was being pressed for 30 minutes at a temperature of +20°C using a pneumatic clamping machine. Technological exposure after bonding was 7 days. The next stage was the formation of samples of the appropriate shape and size according to the DSTU EN 205:2014 standard (2014). The dimensions of the experimental sample were 150x20x10 mm (Fig. 1).

a)

b)

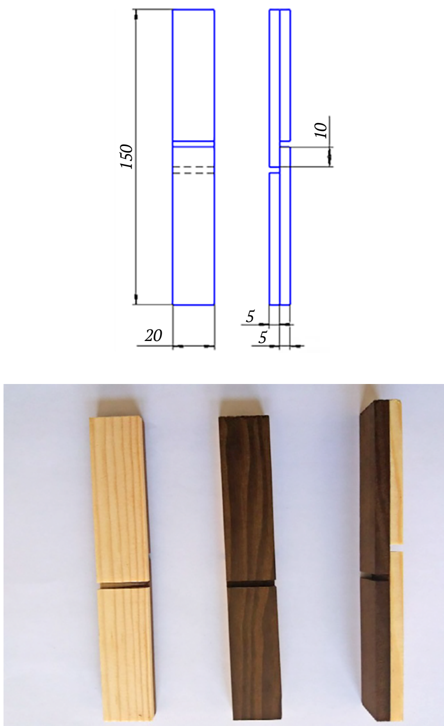

Figure 1. Diagram and samples for determining the strength of the adhesive joint of thermally modified ash wood and unmodified pine wood (a) sample diagram; b) experimental samples)

Source: compiled by the authors

Methodology for conducting long-term experimental studies. A long-term (natural) method was used to examine the strength of adhesive joints of thermally modified ash wood and unmodified pine wood, which allows for assessing the change in the strength of adhesive joints of wood under the influence of atmospheric factors. This method of research is time- and labour-consuming, but more reliable. The results obtained using the long-term method allow considering the real impact of natural factors.

The shapes and sizes of the samples met the DSTU EN 205:2014 standard (2014). Before the study, a stand was made for testing samples, a glue was prepared, samples were made, a stand was installed, and the samples were fixed on it (Fig. 2).

Figure 2. Stand for testing experimental samples in atmospheric conditions

Source: compiled by the authors

All the experimental samples that were used for long-term studies were divided into two parts. One part of the samples was placed on the test stand in atmospheric conditions according to the requirements described above, and the other part was used as controls that were not exposed to natural factors and were used to determine the initial strength of adhesive joints. The number of samples in one batch was determined by the conditions for conducting experimental studies.

The prepared samples were placed on a stand shelf at a distance of 20 mm from each other to ensure air circulation. The stand with the samples was fixed at a height of three meters from the ground level. The studies in atmospheric conditions were conducted for two years. Every three months from the start of the study, namely after 3, 6, 9, 12, 15, 18, 21, and 24 months, a batch of samples was removed from the stand and subjected to tests.

Changes in atmospheric factors (average daily humidity and ambient temperature) were recorded during the entire experiment. In addition, changes in the appearance of the samples, of their size and shape were periodically recorded.

The strength of adhesive joints of thermally modified ash wood and unmodified pine wood glued with thermoplastic glue was determined by stretching along fibres with a constant load (50 mm/s). The long-term testing of the samples was conducted on a breaking machine of the R-05 brand (Fig. 3). The results obtained after the long-term tests were recorded in the observation log. After that, statistical processing was performed on the basis of which graphical dependencies were constructed.

Figure 3. Breaking machine R-05

Source: compiled by the authors

Results and Discussion

The obtained results of the experimental studies on the strength of adhesive joints of thermally modified ash wood and unmodified pine wood by using the long-term method are presented in Table 1.

Table 1. Strength of thermally modified ash wood and unmodified pine wood glued with polyvinyl acetate adhesives

No.	Adhesive joint strength, MPa								
	Initial strength	Duration of experiment, months							
		3	6	9	12	15	18	21	24
1	7.05	5.95	6.00	4.80	5.00	5.55	4.75	6.75	5.50
2	6.55	6.90	6.15	6.25	5.50	4.80	6.80	5.75	4.75
3	8.25	5.63	6.25	4.75	7.63	6.75	5.50	6.65	4.50
4	6.75	5.85	8.00	5.00	6.65	5.80	6.75	4.80	6.00
5	6.00	6.38	6.75	6.25	5.50	5.30	5.50	5.00	5.50
6	6.85	6.25	6.85	7.37	5.50	5.60	5.75	6.25	4.35
7	7.25	6.85	5.40	4.74	7.00	7.00	6.50	5.00	4.74
8	7.00	6.25	6.75	7.75	7.00	6.05	5.40	5.45	6.25
9	7.65	6.55	5.60	5.50	6.50	5.75	5.75	5.45	5.00
10	7.65	7.20	6.75	4.75	4.75	5.95	5.25	6.25	5.25
11	6.75	6.25	5.50	5.25	7.00	5.75	7.25	5.50	5.75
12	6.00	6.15	7.35	7.00	4.00	4.70	5.75	4.50	4.45
13	8.00	5.00	6.00	4.50	5.50	5.65	7.00	5.75	6.00
14	7.25	6.50	7.75	6.75	6.50	6.25	5.35	5.15	5.00

Table 1, Continued

No.	Adhesive joint strength, MPa								
	Initial strength	Duration of experiment, months							
		3	6	9	12	15	18	21	24
15	8.35	5.80	7.10	6.75	4.50	6.50	5.25	6.00	6.00
16	6.90	5.25	7.10	4.75	6.00	5.50	6.50	5.15	4.45
17	6.55	6.25	8.25	7.25	5.25	6.25	6.25	5.25	4.50
18	7.25	7.11	6.60	7.75	4.21	6.05	6.50	5.75	5.75
19	6.40	5.70	5.00	4.75	6.00	6.65	5.50	5.25	5.50
20	8.00	7.11	6.50	5.75	6.25	5.25	6.30	6.35	4.50
21	7.55	5.50	6.20	7.00	6.25	5.80	5.75	6.00	4.10
22	6.95	6.20	5.75	6.00	4.75	6.15	6.25	5.35	4.30
23	6.78	6.80	7.75	7.50	7.25	6.65	5.75	5.75	5.50
24	6.95	7.55	6.50	6.25	5.45	6.10	4.75	5.35	4.50
25	7.25	7.50	6.25	6.75	5.25	5.05	6.25	6.10	6.00
Avg.	**7.12**	**6.34**	**6.56**	**6.05**	**5.81**	**5.87**	**5.93**	**5.62**	**5.13**

Source: compiled by the authors

Figure 4 shows a graphical interpretation of changes in the average strength of thermally modified ash wood and unmodified pine wood during two years of natural testing.

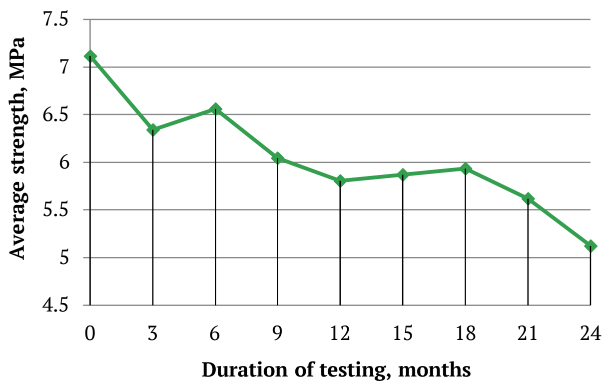

Figure 4. Change in the strength of adhesive joints during two years of testing
Source: compiled by the authors

The results of the long-term experimental studies–on the strength of adhesive joints of thermally modified ash wood and unmodified pine wood glued with thermoplastic polyvinyl acetate adhesives showed that the change in the strength of such adhesive joints occurs along a sinusoidal curve. Namely, the average strength of the control samples is 7.12 MPa. The average strength after 24 months of testing decreased to 5.13 MPa, which is 27.9% as a percentage.

This reduction in strength is not critical for adhesively-bonded structures operating in a variable temperature and humidity environment.

The change in the strength of such adhesive joints will be further analysed step by step in more detail according to the methodology of experimental studies, namely every three months of operation in natural conditions. According to the experiment plan, the samples were put in a stand on November 7, 2019. The first batch of the samples was removed from the stand and destroyed three months later. Each subsequent batch was removed similarly every three months after cyclic temperature and humidity tests, namely after 6, 9, 12, 15, 18, 21, and 24 months. According to the tests, the average strength was: 6.34 MPa, 6.56 MPa, 6.05 MPa, 5.81 MPa, 5.87 MPa, 5.93 MPa, 5.62 MPa, 5.13 MPa. That is, the strength decreases gradually with increasing duration of the experiment.

Therewith, as can be seen from Figure 4, the strength of adhesive joints of thermally modified ash wood and unmodified pine wood glued with thermoplastic polyvinyl acetate adhesives varies depending on the time of year. Namely, in the summer, the strength decreases with increasing test duration, which is not observed in winter. As can be seen from the graph, after testing in winter, the strength of adhesive joints does not decrease, but on the contrary, increases slightly. For example, analysing the period from 3 to 6 months of testing, the strength of such a joint changes from 6.34 MPa to 6.56 MPa in three months of testing, which is 0.22 MPa more than the strength that was after 3 months of testing. The same pattern is observed after 15 and 18 months of operation. The strength changes from 5.87 MPa to 5.93 MPa, which is 0.06 MPa higher than the fifteen-month test period.

In accordance with the requirements for wood adhesive joints, the bonding strength after experimental tests is considered satisfactory if its numerical value decreases by less than 50%. In this case, this requirement is observed. Therefore, it can be assumed that the adhesive bonding of thermally modified ash wood and unmodified pine wood glued with thermoplastic polyvinyl acetate adhesives can be used for structures that will be operated in a variable temperature and humidity environment without any physical stress.

However, the strength of such adhesive joints is lower than that of unmodified ash wood with unmodified pine wood. The strength of such adhesive joints, according to the previous studies, should be within the strength limits of pine wood.

The behaviour of such an adhesive bonding can be explained by physical and chemical changes in thermally modified ash wood caused by the action of elevated temperatures. Namely, the action of temperature leads to the breakdown of hemicellulose and cellulose to form furfural, which affects the bondin g surface of ash wood. Furfural leads to the formation of a smooth bonding surface, which negatively affects the adhesive properties of adhesives and thereby reduces the strength of the adhesive joint. Therewith, the increased temperature leads to a change in the mechanical properties of such wood (Zelinka *et al.,* 2022). That is, it makes it more brittle and changes its structure, which negatively affects the penetration of glue into the wood.

B. Kshyvetskyy *et al.* (2019) note that glueing is one of the most common types of wood bonding used in the manufacture of joinery boards, furniture boards, facing panel materials, window and door blocks, floor coverings, etc. This method of joining is based on the phenomena of adhesion, that is, the ability to form various kinds of bonds between glue and wood.

Adhesives for gluing thermally modified wood, which would provide proper adhesive strength under operating conditions, currently practically do not exist. Therefore, there is a problem with gluing thermally modified wood and finding new adhesives.

A. Can *et al.* (2021) examined the strength of adhesive joints of thermally modified pine, which was first dried at a temperature of 103°C, and then modified in the temperature range from 190°C to 212°C for 2 hours. Polyvinyl acetate glue with a 195.54 hardener was used to form the adhesive joint. The strength of such adhesive joints decreased by 31-39% compared with the initial strength. H.R. Taghiyari (2013) concluded that this change in strength occurs due to a decrease in the wetting index, oxidation of the wood surface, changes in the chemical and physical properties of wood, and a substantial decrease in the number of polar groups.

M. Ilkiv *et al.* (2017) investigated the strength of adhesive joints of thermally modified ash wood glued with polyvinyl acetate glue. Thermal modification of wood was conducted for 4 hours at a temperature of 160°C and 220°C. The strength of the adhesive joints of the treated ash wood at a temperature of 160°C is 3.45 MPa, and at a temperature of 220°C – 6.34 MPa. The authors explain this change in strength through physical and chemical changes that occur in the wood when exposed to high temperatures. The increase in strength occurs due to an increase in the lignin content due to the crosslinking reaction. This creates more intermolecular bonds between the wood and the adhesive.

Z. Vidholdová *et al.* (2021) investigated the strength of adhesive joints of thermally modified spruce, which was dried at a temperature of 100 °C, and then subjected to thermal modification at temperatures of 160°C, 180°C, 200°C, and 220°C for 4 hours. Polyvinyl acetate and polyurethane adhesives were used for bonding. Forming adhesive joints, dried wood and thermally modified wood were combined. The bonded structures made only from thermally modified wood showed a substantial reduction in strength compared to the bonded structures that were formed from dried wood and thermally modified wood. The authors concluded that this change in strength is associated with the degradation of amorphous polysaccharides under the influence of high temperatures, which leads to a decrease in the number of polar groups in the cell walls of the wood.

Similar results for bonding thermally modified wood are also presented in the papers (Uzun *et al.*, 2016; Andromachi & Ekaterini, 2018; Taghiyari *et al.*, 2020). The authors noted that the decrease in strength is affected by wetting ability, microcracks, density, surface of thermally modified wood, and the physical-chemical characteristics of the adhesive.

The results were obtained using two methods, namely: long-term (natural) and accelerated (laboratory). As for the first long-term research method, it was conducted for the first time and deserves special attention, since it was conducted in the natural conditions of the Western region of Ukraine for two years. The obtained results reflect the factual behaviour of such adhesive joints under prolonged varying temperature and humidity loads. Therewith, the results of the studies of changes in the strength of adhesive joints of thermally modified ash wood and unmodified pine wood allow for building a mathematical model for predicting strength from the action of ambient temperature and humidity in the future. The accelerated method of experimental studies using various types of wood, especially thermally modified wood, is rare in adhesive structures. In the studies (Biazzon *et al.* 2019; Chang *et al.* 2019; Can *et al.* 2021;), the authors examined changes in the strength of adhesive joints of several-species of wood, using various adhesive materials, including polyvinyl acetate composition. Therefore, this experimental study cannot be compared with the results obtained by other authors, since they had different research conditions, namely the temperature of thermal modification of wood, test conditions, etc. In general, it can be noted that the dynamics of changes in the strength of adhesive joints in this study and studies by other authors occur according to similar dependencies.

Conclusions

Based on the results of long-term experimental studies of the strength of adhesive joints of thermally modified ash wood and unmodified pine wood glued with thermoplastic polyvinyl acetate adhesives, the following can be concluded:

1. A method for conducting long-term experimental studies in natural conditions was selected for thermoplastic polyvinyl acetate adhesive joints of thermally modified ash wood and unmodified pine wood based on Ukrainian and foreign standards. Samples were prepared for experimental studies.

2. It was found that the strength of adhesive joints of thermally modified ash wood and unmodified pine wood decreased by 27.9% after two years of testing and long-term experimental studies. Namely, it decreased from 7.12 MPa to 5.13 MPa.

3. It was found that the change in the strength of adhesive joints of thermally modified ash wood and unmodified pine wood in different periods of operation does not change in the same way, namely, in summer, the strength decreases in a descending curve depending on the duration of operation, and in winter, this pattern is disrupted since the strength does not decrease, but on the contrary, increases. On average, it increases by 1%.

4. Based on the results of the long-term experimental studies, it was found that adhesive joints of thermally modified ash wood and unmodified pine provide operational characteristics in a variable temperature and humidity environment.

In the future, it is planned to conduct studies on the strength of adhesive joints of other species of thermally modified wood.

Conflict of Interest

The authors declare no conflict of interest.

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None.

References

[1] Afshar, R. (2022). Characterisation of mechanical properties of wood: Size effect. In *Theoretical analyses, computations, and experiments of multiscale materials* (pp. 659-669). Berlin: Springer. doi: 10.1007/978-3-031-04548-6_30.

[2] Andromachi, M., & Ekaterini, R. (2018). Adhesive bond performance of heat-treated fir wood (*Abies Borrissiregis*). *Wood Research*, 63(5), 909-916.

[3] Biazzon, J.C., Junior, M.L., Munis, R., & Araujo, V. (2019). Shear strength of eucalyptus saligna wood joints bonded with polyvinyl acetate adhesive. *Bioresources*, 14(2), 4590-4602. doi: 10.15376/biores.14.2.4590-4602.

[4] Budhe, S., Banea, M.D., Ghugal, S., & Barros, S. (2020). Effects of heat treatment on the behavior of teak wood adherends bonded joints. *Applied Adhesion Science*, 8, article number 1. doi: 10.1186/s40563-020-00124-5.

[5] Can, A., Krystofiak, T., & Lis, B. (2021). Shear and adhesion strength of open and closed system heat-treated wood samples. *Maderas: Ciencia y Tecnologia*, 23. doi: 10.4067/s0718-221x2021000100432.

[6] Candelier, K., Hannouz, S., Thévenon, M.-F., Guibal, D., Gérardin, P., Pétrissans, M., & Collet, R. (2017). Resistance of thermally modified ash (*Fraxinus excelsior* L.) wood under steam pressure against rot fungi, soil-inhabiting micro-organisms and termites. *European Journal of Wood and Wood Products,* 75(2), 249-262. doi: 10.1007/s00107-016-1126-y.

[7] Chang, C.-W., Kuo, W.-L., & Lu, K.-T. (2019). On the effect of heat treatments on the adhesion, finishing and decay resistance of japanese cedar (*Cryptomeria japonica* D. Don) and Formosa acacia (*Acacia confuse* Merr.(Leguminosae)). *Forests*, 10(7), article number 586. doi: 10.3390/f10070586.

[8] Datskiv, H.M., & Kshyvetskyy, B.Ya. (2020). Methodology for conducting experimental studies on the strength of joints of thermally modified wood glued with PVA-based adhesives. *Proceedings of the Xth International scientific and practical conference "Complex quality assurance of technological processes and systems"*, 1, article number 202.

[9] DSTU EN 205:2014 "Adhesives for glueing wood which is not subjected to power loads. A method for determining the strength of a lap joint during longitudinal shear tension" (EN 205:2003, IDT). (2014). Kyiv: Derzhspozhyvstandart Ukrainy.

[10] Giridhar, B.N., & Pandey, K.K. (2022). Wood modification for wood protection. In *Science of Wood Degradation and its Protection* (pp.647-663). Berlin: Springer. doi: 10.1007/978-981-16-8797-6_19.

[11] Hill, C., Altgen, M., & Rautkari, L. (2021). Thermal modification of wood – a review: chemical changes and hygroscopicity. *Journal of Materials Science*, 56, 6581-6614. doi: 10.1007/s10853-020-05722-z.

[12] Ilkiv, M.M., Solonynka, V.R., Humeniuk, Zh.Ya., & Huber, Yu.M. (2017). The study on the strength of adhesive joints of thermally modified ash wood obtained by the technology of vacuum-conductive heat treatment. *Scientific Bulletin of UNFU*, 27(3), 136-139. doi: 10.15421/40270330.

[13] Jones, D., & Sandberg, D. (2020). A review of wood modification globally – updated findings from COST FP1407. *Interdisciplinary Perspectives on the Built Environment (IPBE)*, 1, 1-31. doi: 10.37947/ipbe.2020.vol1.1.

[14] Kozakiewicz, P., Drożdżek, M., Laskowska, A.K., & Grzeskiewicz, M. (2020). Chemical composition as a factor affecting the mechanical properties of thermally modified black poplar (*Populus nigra* L.). *Bioresources,* 15(2), 3915-3929. doi: 10.15376/biores.15.2.3915-3929.

[15] Král, P., Klímek, P., & Děcký, D. (2015). Comparison of the bond strength of oak (*Quercus* L.) and beech (*Fagus sylvatica* L.) wood glued with different adhesives considering various hydrothermal exposures. *Journal of Forest Science,* 61(5), 189-192. doi: 10.17221/95/2014-JFS.

[16] Kristak, L., Réh, R., & Kubovský, I. (2021). New challenges in wood and wood-based materials. *Polymers*, 13(15), article number 2538. doi: 10.3390/polym13152538.

[17] Kshyvetskyy, B.Ya., Datskiv, H.M., & Andraszek, Y.V. (2019). General information about adhesives, bonding and thermally modified wood. *Scientific Bulletin of UNFU*, 29(3), 81-84. doi: 10.15421/40290317.

[18] Li, Y., Case, S.W., & Lattimer, B.Y. (2021). Measurement and modelling of thermal and physical properties of wood construction materials. *Construction and Building Materials*, 284, article number 122780. doi: 10.1016/j.conbuildmat.2021.122780.

[19] Repič, R., Pondelak, A., Kržišnik, D., Humar, M., & Škapin, A.S. (2022). Combining mineralisation and thermal modification to improve the fungal durability of selected wood species. *Journal of Cleaner Produktion*, 351, article number 131530. doi: 10.1016/j.jclepro.2022.131530.

[20] Sandberg, D., Kutnar, A., & Mantanis, G.I. (2017). Wood modification technologies – a review. *iForest – Biogeosciences and Forestry*, 10(6), 895-908. doi: 10.3832/ifor2380-010.

[21] Taghiyari, H.R. (2013). Effects of heat-treatment on permeability of untreated and nanosilver-impregnated native hardwoods. *Maderas. Ciencia y Tecnología,* 15(2), 183-194. doi: 10.4067/S0718-221X2013005000015.

[22] Taghiyari, H.R., Esmailpour, A., Adamopoulos, S., & Zereshki, K. (2020). Shear strength of heat-treated solid wood bonded with polyvinyl-acetate reinforced by nanowollastonite. *Wood Research*, 65(2),183-194. doi: 10.37763/wr.1336-4561/65.2.183194.

[23] Uzun, O., Percin, O., Altinok, M., & Kureli, I. (2016). Bonding strength of some adhesives in heat-treated hornbeam (*Carpinus betulus* L.) wood used of interior and exterior decoration. *Bioresources*, 11(3), 7686-7696. doi: 10.15375/biores.11.3.7686-7696.

[24] Vidholdová, Z., Ciglian, D., & Reinprecht, L. (2021). Bonding of the thermally modified norway spruce wood with the pur and pvac adhesives. *Acta Facultatis Xylologiae Zvolen*, 63, 63-73. doi: 10.17423/afx.2021.63.1.06.

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

[26] Zigon, J., Wålinder, M., & Moghaddam, M.S. (2022). Wettability and surface interactions of natural and thermally modified beech wood with water and water-based coatings: The effect of surface pre-treatment type. *European Journal of Wood and Wood Products*, 81, 73-88. doi: 10.1007/s00107-022-01875-7.

Результати експериментальних досліджень міцності клейових з'єднань термічно модифікованої деревини ясена

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Анотація. Для покращення експлуатаційних властивостей та підвищення довговічності клейовим деревинним конструкціям необхідно забезпечити їх захист від дії впливу температурно-вологісних навантажень, що і зумовлює актуальність цього дослідження. Метою роботи було дослідження міцності термопластичних клейових з'єднань термічно модифікованої деревини ясена і сосни немодифікованої за тривалим методом. Дані піддавались статистичній обробці та аналізу. Експериментальні зразки для дослідження були підготовлені згідно з запропонованою методикою у виробничих умовах відповідно до існуючого технологічного процесу. Дослідження тривали протягом двох років з періодичним оглядом зразків та фіксацією змін, які проходили під час випробувань. Регулярно після кожних трьох місяців досліджень частину зразків знімали зі стенду і проводили випробування для визначення зміни міцності. Підібрано та описано методику проведення тривалих експериментальних досліджень з визначення міцності клейових з'єднань термічно модифікованої деревини ясена і сосни немодифікованої, клеями на основі полівінілацетату із класом довговічності D4. За результатами досліджень встановлено, що середня міцність контрольних зразків термічно модифікованої деревини ясена і сосни немодифікованої становила 7,12 МПа, а після двох років тривалих випробувань зменшилась до 5,13 МПа (27,9 %). Крім того встановлено, що експлуатація таких клейових з'єднань у природних умовах залежить від циклічного температурно-вологісного навантаження. А саме, у літньо-осінній період міцність зменшується, а зимово-весняний залишається незмінною а в деяких випадках і підвищується. Отримані результати досліджень мають важливе практичне значення, оскільки такі клейові конструкції, можуть використовуватись для виготовлення столярно-будівельних виробів, що дозволить підвищити їх експлуатаційні характеристики та збільшити довговічність

Ключові слова: тривалий метод; сосна; атмосферні фактори; температурно-вологісні навантаження; довговічність, адгезія

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UAV data collection parameters impact on accuracy of Scots pine stand mensuration

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Abstract. A wide range of UAV systems used for forest research requires unified approaches to data collection. The research aims to determine the optimal parameters for UAV data collection to obtain accurate information about stands, considering the cost of resources for its collection. The process of collecting remote sensing data consisted of nine combinations divided into three levels of overlap and three levels of spatial resolution (survey altitude) and changing the degree of filtering of a dense point cloud during image processing. Individual tree detectingin the stand was performed using the R programming language and the ForestTools package. The results of the assessment of the dependence of the radius of tree crowns on their height were used to set the parameters of the variable filter function for finding local maxima for Scots pine stands. Errors in the identification of treetops were estimated using the *F-score*. The identified heights were compared with the field data of the ground survey. The proportion of classified digital elevation model DEM in the dense point cloud was reduced from the total area of the test site using images of 4.1 cm/pix spatial resolution (150 m survey altitude). The study presents the results of assessing the impact of spatial resolution of optical images collected from UAVs and their overlap on the results of measurements of stands parameters. It is determined that a photogrammetric survey with input images with a longitudinal overlap of less than 90% is not appropriate for the study of forest areas due to the impossibility of aligning all images. The results of the assessment of tree accounting in the stand showed that it is most appropriate to use images with a spatial resolution of up to 3.3 cm/pix (120 m survey altitude), otherwise, the proportion of missed treetops increases. Reducing the spatial resolution of remote sensing data leads to an increase in errors in determining the height of individual trees, and the average heights of the experimental plots had the same trend. Given the combination of the assessed

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factors, it is not recommended to use images with a spatial resolution of more than 3.3 cm/pix for forestry research due to increased errors in the individual tree detection and tree height determination. The results obtained can be used to select data collection parameters for research on Scots pine stands to assess their growing stock and phytomass

Keywords: photogrammetry; canopy height model; individual tree detection; height determination; digital elevation model

Introduction

Remote sensing data is used in forestry to reduce the economic costs of operations and increase their efficiency (McRoberts & Tomppo, 2007). The availability of remote sensing data as an auxiliary material allows the performing of several tasks in forestry, eliminating the need to go to the field. However, there is always a need to estomate indicators of trees and stands for which field ground measurements are required. I. Korpela (2004) pointed out that field inventory data is essential for remote sensing and is used for training, calibration, and verification of results.

First of all, remote sensing data collection systems can be divided into the following categories by type of carrier: satellites, manned aircraft, unmanned aerial vehicles (fixed-wing or multi-rotor), and ground-based scanning systems (Pádua *et al.*, 2017). The use of different types of systems significantly increases the variability of data acquisition methods, and each of them has its advantages and disadvantages. J. White *et al.* (2016), V. Myroniuk *et al.* (2022) in their works, they noted that the use of satellite data in forestry is quite promising since such data cover large areas and can be widely used in forest inventory.

Data from unmanned aerial vehicles have several significant differences compared to satellite imagery: relative cheapness and accessibility, short data collection times, and the ability to obtain high-resolution data. A. Graham *et al.* (2020) described that the development of computing technologies has led the use of *digital aerial photogrammetry*. *Structure-from-motion* technologies are used to reconstruct 3D scenes, including for forestry research and assessment parameters of forest stand (Westoby *et al.*, 2012).

K. Stereńczak *et al.* (2020) described that to determine the individual trees attributes in a stand based on remote sensing data, it is necessary to detect them. A separate large group of works can be distinguished that are devoted to assessing the quality of individual tree detection using a wide range of methods (Duncanson *et al.*, 2014). During classical forestry surveys, the processes of accounting for the number of trees and determining their parameters can be separated: it is possible to determine the tree parameters without their continuous accounting on the site. It is impossible to determine the individual trees parameters based on digital aerial photogrammetry or LiDAR (Light Detection and Ranging) data without their detecting. Therefore, the identification of individual trees in a stand is an essential step in estimating their attributes (Mohan *et al.*, 2021). The number of tree parameters that can be estimated will depend on the applied detecting algorithms and the characteristics of the input remote sensing or scanning data (Guimarães *et al.*, 2020). The use of a local maximum filter is one of the simplest methods of tree detecting and measuring their height (Popescu & Wynne, 2004; Silva *et al.*, 2022).

K. Ma *et al.* (2022) found that the quality of individual trees detection in a stand is influenced by several factors: morphological features of the studied stands (tree crown shape, stand structure), selection of remote sensing data collection parameters, and remote sensing data processing parameters. Considering the morphological factor, it was found that the structure of forest stands significantly affects the quality of tree detection and delineation. The use of LiDAR data makes it possible to study the three-dimensional structure of forest stand under the canopy of the dominant trees, but the results of detection in the second or third tiers do not give satisfactory results (Ferraz *et al.*, 2012).

Methods of tree detection are constantly evolving to achieve better results, and the high accuracy of measuring the height of stands based on remote sensing data has been confirmed by several studies (Ota *et al.*, 2017; Guimarães *et al.*, 2020). The use of remote sensing methods is most promising in coniferous stands, as they are the most easily decipherable (Heurich, 2008). In Ukraine, where coniferous plantations occupy a significant share, the introduction of remote sensing methods is a very promising direction. The height of Scots pine stands can be determined with sufficient accuracy based on photogrammetric survey data compared to classical measuring instruments (Bilous *et al.*, 2021).

Remote sensing data acquisition parameters affect the characteristics of the resulting dense point cloud, which affects the accuracy of tree attributes measuring and the possibility of their further application (Kameyama & Sugiura, 2021).

The research aimed to determine the optimal parameters for collecting data from UAVs to obtain sufficiently accurate information about forest stands.

Materials and Methods

The study was carried out in August 2020 on the territory of the Chornobyl Exclusion Zone, where plantations have been formed over the past decades without active (significant) anthropogenic intervention. The study was carried out on an 18.5-hectare polygon with eight circular sample plots. The experimental site was selected in such a way as to ensure the presence of the most contrasting stands in one remote sensing data collection (Table 1).

Table 1. Characteristics of the experimental stands

Sample plot, No	Area, m^2	Origin	Age, years	Number of trees in the site	Average diameter, cm	Average height, m	Site index
1	250	Artificial	58	46	18.3	20.8	I
2	100	Artificial	58	56	8.2	8.2	V
3	1000	Natural	50	30	11.5	7.3	V
4	250	Artificial	58	42	13.2	11.7	IV
5	100	Artificial	70	38	10.5	10	V
6	250	Artificial	58	59	16.8	21.7	I
7	100	Artificial	58	42	11.6	15.1	III
8	50	Artificial	58	62	4.6	5.4	Va

Source: compiled by the author

As a result of the dramatic change in habitat conditions, the experimental sites had different stands in terms of diameter, height, and number of trees per hectare. The size of the sample plots depends on the density of the trees and is set to ensure that there are at least 30 trees per plot. The spatial location of the trees in the sample plots were established using a *TruPulse* 360B laser-optical rangefinder and *MapSmart* software, with measurements of tree diameter at 1.3 m, height of model trees, tree species and live status. All trees that reached a height of 1.3 m without any minimum diameter restrictions were selected for the ground survey. For the assessment quality of individual tree detection, we used the trees occupying the highest position in the stand and their tops position on orthophoto maps. Heights were measured for 10 model trees in artificial stands and 17 in natural stands. The age of the stands was determined based on forest management materials (Mensuration description..., 2016), and for the natural stands, the age was determined by counting annual rings selected using a *Haglof* increment borer.

A *Phantom 4 Pro* UAV was used for remote sensing, equipped with a 1 "CMO" camera with a 20-megapixel matrix. The input data for remote sensing are a series of UAV images obtained at different shooting altitude and overlaps. Flight planning and surveying of the test polygon were performed using *Pix4Dcapture* software. An estimate of the time spent on collecting remote sensing data, and quantitative and qualitative characteristics of the input image series is given in Table 2.

Table 2. Quantitative characteristics and timing of UAV data collection

Combination number	Survey altitude, m	Longitudinal (transverse) overlap, %.	Record time, min:sec	The number of pictures, pcs.	UAV flight distance, m	Picture resolution, cm/pix
1	80	90(81)	21:06	513	4296	2.18
2	80	80(72)	11:01	209	3529	2.18
3	80	70(63)	06:52	129	2805	2.18
4	120	90(81)	15:24	329	4282	3.27
5	120	80(72)	08:14	125	2929	3.27
6	120	70(63)	07:01	95	3107	3.27
7	150	90(81)	12:07	233	3771	4.09
8	150	80(72)	07:30	102	2868	4.09
9	150	70(63)	07:00	82	2871	4.09

Source: compiled by the author

Photogrammetric image processing was performed using specialized *Metashape* software. During the processing of each of the individual series of images, iterations of their alignment and the creationof a dense point cloud were performed using identical processing parameters. For each iteration, two dense point clouds were built: one with an aggressive degree of filtering and one with a soft degree. Next, the ground points of the dense cloud were classified, based on which a digital elevation model (DEM) was built, and a digital surface model (DSM) was created based on all cloud points. The original raster materials were exported in the metric coordinate system with a spatial resolution of 15 cm/pix. Visual analysis and aggregation with ground data were performed in the QGIS (Quantum GIS) geographic information system, where the canopy height model (CHM) was calculated using formula (1):

$$CHM=DSM-DEM \qquad (1)$$

At the first stage of the study, the quality of terrain classification of the dense point cloud used to create the DEM was assessed. To do this, the proportion of the terrain classified to the total area of the polygon was determined. The area of classified terrain was defined as the sum of pixels of the DEM generated without interpolation.

Individual tree detection using algorithms in the R programming language with the use of the local maximum search function implemented in the {ForestTools} package (Plowright, 2020). This function uses a local maximum search filter, which is necessary to limit the search radius between potential treetops. This filter can be set to a fixed search radius or given a variable radius function. The advantage of the variable radius filter is that after identifying the treetop, it takes the height value as an independent variable and determines the potential radius of the tree crown (Popescu & Wynne, 2004). Considering that the experimental polygon contains sample plots with different stand parameters, a variable radius filter was applied.

The crown radius of Scots pine was determined from the collected remote sensing data using UAVs. Based on the formed array of 380 Scots pines, a logarithmic dependence of the crown radius of trees on their height within the experimental polygon was established (formula 2). The computed confidence interval at the level of 2.5% for parameters of the established regression was used to describe the lower level dependence of the crown radius to tree height. Thus, the variable search radius filter was assigned the expression of the established confidence interval for parameters of level 2.5% (formula 3).

$$rF=0{,}369 \cdot ln(\mathrm{h})+0{,}421, \qquad (2)$$

$$rF(2{,}5\%)=0{,}297 \cdot ln(\mathrm{h})+0{,}221, \qquad (3)$$

where rF is the established search radius (tree crown radius), m; $rF_{(2.5\%)}$ is the lower confidence interval of the model parameters; h is the height of the tree, m.

The *CHM* smoothing was performed to test whether it is possible to achieve better tree detection results by avoiding the identification of false tops caused by tree branches (Mohan *et al.*, 2017). The detection was performed with and without smoothing the image using a 5x5 pixel Gaussian filter. The {rLiDAR} package in the R programming language was used to smooth CHM rastes.

In a geographic information system, the detected tops are compared with ground-measured data and an orthophoto map of the sample plots (Fig. 1).

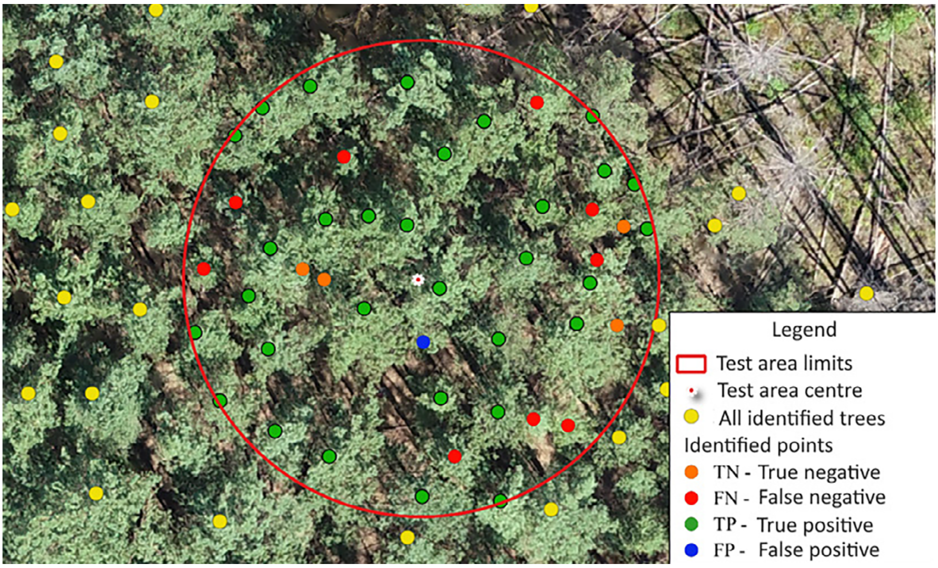

Figure 1. A confusion matrix of tree detection quality assessment in sample plot No. 1
Source: compiled by the author

The quality of individual tree detecting was assessed using confusion matrix. Twelve iterations of detecting were compared, the identified treetops were assigned the TP status, and the missed ones were assigned the FN status. Falsely identified tops during the comparison of each iteration were assigned the FP status (Table 3).

Table 3. Confusion matrix indicators and andividual tree detecting accuracy values

CHM type	Number of treetop	TP	FP	FN	Recall	Precision	F-score	FNR	FDR
a80	246	172	23	74	0.70	0.88	0.78	0.30	0.12
a80SMTH	246	165	10	81	0.67	0.94	0.78	0.33	0.06
m80	246	168	24	78	0.68	0.88	0.77	0.32	0.13
m80SMTH	246	164	12	82	0.67	0.93	0.78	0.33	0.07
a120	246	166	23	80	0.67	0.88	0.76	0.33	0.12
a120SMTH	246	155	10	91	0.63	0.94	0.75	0.37	0.06
m120	246	178	40	68	0.72	0.82	0.77	0.28	0.18
m120SMTH	246	168	28	78	0.68	0.86	0.76	0.32	0.14
a150	246	135	9	111	0.55	0.94	0.69	0.45	0.06
a150SMTH	246	129	6	117	0.52	0.96	0.68	0.48	0.04
m150	246	138	9	108	0.56	0.94	0.70	0.44	0.06
m150SMTH	246	133	7	113	0.54	0.95	0.69	0.46	0.05

Note: "80, 120, 150" = shooting height, "a, m" = dense cloud filtering parameters (aggressive, soft), SMTH = CHM raster was smoothing
Source: compiled by the author

The accuracy indicator of tree detecting was the F-score, calculated based on Recall (produser's accuracy) and Precision (user's accuracy) according to uations (4)-(6). The comparison of errors arising from the use of different CHM rasters was performed using the False Negative Rate (FNR) and the False Discovery Rate (FDR) according to equation (7), and (8) (Maxwell *et al.*, 2021).

$$r = \frac{TP}{TP+FN}, \quad (4)$$

$$p = \frac{TP}{TP+FP}, \quad (5)$$

$$F = \frac{2*r*p}{r+p}, \quad (6)$$

$$FNR = \frac{FN}{TP+FN}, \quad (7)$$

$$FNR = \frac{FP}{TP+FP}, \quad (8)$$

where *TP* is the number of true positive detected treetops, *FN* is the number of false negatives, and *FP* is the number of false positives.

The heights of the trees are measured by detecting their tops. The algorithm assigns the height value of a cell from the CHM raster to each detected local maximum (Plowright, 2020). Thus, the results of the top detecting are used to measure the heights of individual trees and calculate the average height in the sample plots.

The estimation of tree height errors was used to determine the influence of UAV data collection parameters on the distribution of CHM heights. To compare the results of measuring the height of individual trees with different data collection parameters, the local maxima of identified trees were selected with their height parameters. The sample included trees for which ground-based height measurements were available and local maxima were detected during all iterations of the survey. For the purpose of comparing average height measurements, the results obtained from detecting all treetops in sample plots were utilized, and the average height was calculated based on the ground data.

The root means square and *Bias* were used to assess the accuracy of the remote sensing method for height measure (Su *et al.*, 2020; Holiaka *et al.*, 2021). The heights determined by the remote sensing method are compared with the ground survey data using formulas (9)-(12).

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(\hat{y}_i - y_i)^2}{n}}, \quad (9)$$

$$RMSE\ (\%) = 100 \cdot \frac{RMSE}{\bar{y}}, \quad (10)$$

$$Bias = \frac{\sum_{i=1}^{n}(\hat{y}_i - y_i)}{n}, \quad (11)$$

$$Bias\ (\%) = 100 \cdot \frac{Bias}{\bar{y}}, \quad (12)$$

where $\hat{y}_i$ – the value determined remotely, y_i – the value according to the ground survey, and $\bar{y}$ – the arithmetic mean.

Results and Discussion

During the photogrammetric processing, the image arrays with less than 90% overlap could not be aligned, which makes further analysis impossible. The exception is combination No. 8 (altitude 150 m), where all images with a longitudinal overlap of 80% were aligned. Thus, remote sensing data of forest stands collected with a longitudinal overlap of less than 90% and a survey altitude of up to 150 m are rather difficult to process photogrammetrically.

Estimating the proportion of the DEM area to the total polygon area at an acquisition altitude of 80 m, the proportion of classified terrain is 59%, at 120 m it is also 59%, at 150 m it is 52% and at the same height with reduced overlap 42%. Part of the polygon had an open area where there were no problems with determining the ground level. Reducing the spatial resolution of the input images significantly reduces the proportion of points in the dense cloud located under the forest canopy, which makes it difficult to form a digital elevation model. DEM classification is quite complicated for closed stands of trees, as well as when there is undercover vegetation.

For remote sensing data collected from altitudes 80 and 120 m, the determinated *F-score* value is in the range of 0.75-0.78. Using the data collected at an altitude of 150 m, the quality of individual tree detection deteriorated significantly, with the *F-score* value in the range of 0.68-0.70. The worst interpretation results were obtained for the sample plot with the V_a site index (sample plot No. 8), which indicates the difficulty of detection the treetops in stands with a dense distribution of low trees.

The error rates that occurred during the identification of the tops are shown in Figure 2. The largest FNR errors were found for CHM models generated from data at a survey altitude of 150 m. A decrease in the proportion of detected treetops indicates that with such data collection parameters, CHM rasters reproduce the structure of stands in less detail.

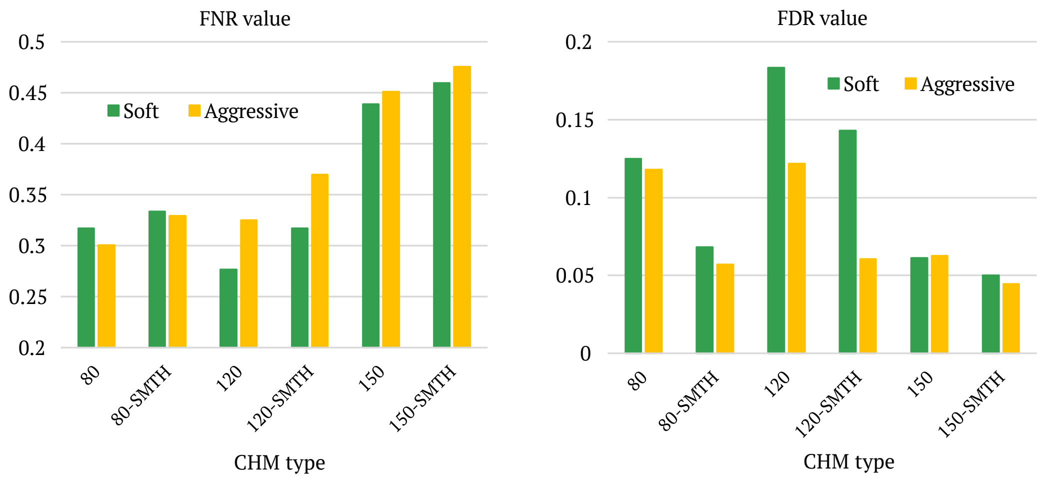

Figure 2. Indicators of tree-top detecting errors

Source: compiled by the author

The error characteristics indicate that the use of a soft degree of filtering during photogrammetry image processing does not reduce the FNR but causes FDR errors. In this case, the use of an aggressive degree of filtering during photogrammetric image processing allows to reduce the proportion of falsely discover local maxima. Smoothing of the CHM raster avoids the occurrence of false detecting treetops but does not affect the overall quality of the peak *F-score*. The data obtained from altitude of 120 m and the soft filter of the dense point cloud allowed us to detected the largest share of the tops, but the worst Precision was obtained due to a significant share of falsely detected tops.

To compare the results of height mensuration, 30 trees were selected. The assessment of the statistical indicators of height mensuration errors indicates that the remote method on average tends to underestimate the height (Table 4, Fig. 3).

Table 4. Errors in measuring the of individual trees height using UAV data

CHM type	*RMSE, m*	*RMSE (%)*	*Bias, m*	*Bias (%)*
a80	0.86	6.71	-0.14	-1.07
a80SMTH	0.91	7.11	-0.31	-2.43
m80	0.82	6.41	-0.16	-1.23
m80SMTH	0.91	7.11	-0.31	-2.43
a120	0.87	6.84	-0.35	-2.72
a120SMTH	0.98	7.66	-0.47	-3.66
m120	0.81	6.32	-0.21	-1.67
m120SMTH	0.83	6.47	-0.34	-2.64
a150	1.28	10.07	-0.95	-7.42
a150SMTH	1.35	10.55	-1.02	-8.00
m150	0.94	7.34	-0.56	-4.39
m150SMTH	0.98	7.67	-0.62	-4.86

Source: compiled by the author

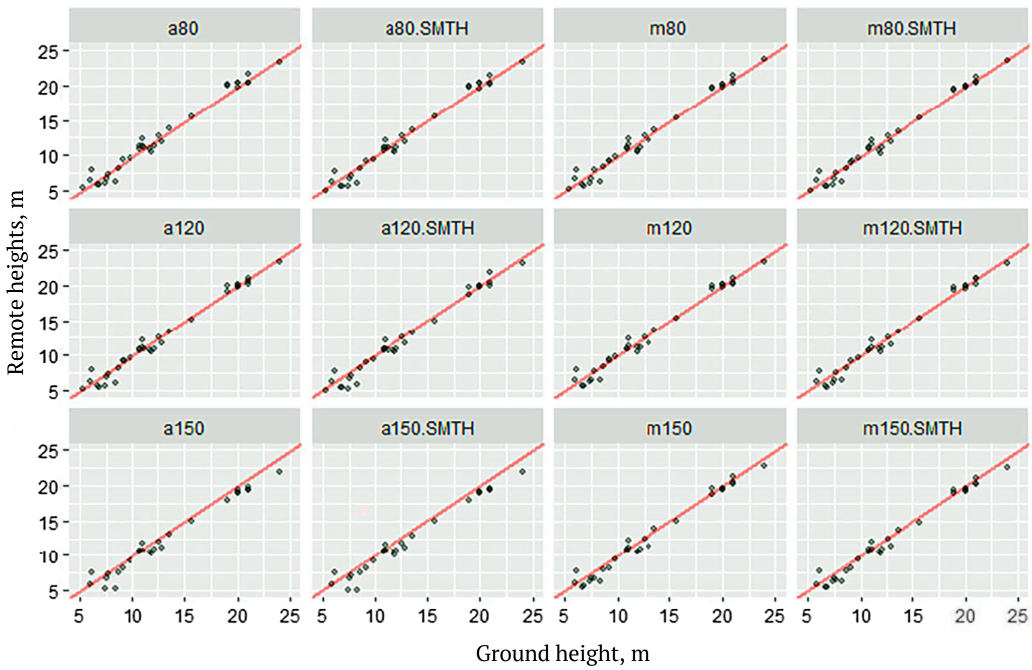

Figure 3. Results of measuring the height of individual trees using CHM data and ground-based methods

Source: compiled by the author

It was found that the underestimation of height is observed for trees up to 10 m in height. For trees with heights of 10-20 m, the remote sensing is comparable to the ground data, while for trees over 20 m in height, the remote sensing data show higher heights. In general, the *Bias* for the models generated from 80 m altitude ranges from -0.1 m to -0.3 m; for the models generated from 120 m altitude, it ranges from -0.2 m to -0.5 m, and the largest deviations are found for the models from 150 m altitude (Fig. 3). This indicates that the data with lower spatial resolution reproduce crown tops worse. To assess the effects of using different remote sensing inputs images in determining the average height, data within the sample plots were used. The average height based on ground data was determined using height curve. The average height from UAV data was calculated as the arithmetic mean of the identified trees in the sample plots (Table 5). Underestimation of the average height by remote sensing is observed for the natural origin of sample plot No. 3 with single low trees.

Table 5. Determined average heights by sample plots and type of data

Type of height determination data	Average heights estimated by sample plots, m							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
a80	21.2	7.3	5.0	10.9	15.0	21.4	11.0	5.4
a80SMTH	20.7	7.3	5.4	10.6	14.7	21.3	10.9	5.4
m80	20.7	8.1	5.7	10.7	14.9	21.2	11.0	5.4
m80SMTH	20.8	7.8	6.1	11.0	14.7	21.2	10.9	5.3
a120	20.5	7.4	5.6	10.9	14.8	21.0	10.9	5.3
a120SMTH	20.3	7.4	5.2	11.0	13.6	21.0	10.8	5.1
m120	20.9	7.7	5.4	10.0	14.2	21.0	11.0	5.2
m120SMTH	21.0	7.5	5.3	9.7	13.8	21.0	11.0	5.2
a150	20.0	7.7	5.6	11.1	13.9	20.2	10.5	5.2
a150SMTH	20.0	7.8	5.4	11.0	14.2	20.1	10.5	5.2
m150	20.7	7.6	5.9	10.7	13.8	20.6	10.9	5.0
m150SMTH	20.7	7.6	5.9	10.7	13.8	20.6	10.9	5.0
Ground (control)	**20.8**	**8.2**	**7.3**	**11.7**	**15.1**	**21.7**	**10.0**	**5.4**

Source: compiled by the author

With the change in CHM, the *RMSE* values for the determined average heights on the sample plots do not differ significantly and are around 1 m for all canopy height models. The *Bias* value for all models is in the range of 3-6%. If we evaluate the change in the *Bias*, we still observe a similar trend as when determining the heights of individual trees, namely, a decrease in the quality of spatial resolution of images leads to an underestimation of the average height (Table 6). The *Bias* value did not exceed 0.5 m for all models from altitude of 80 m and for the aggressive CHM from altitude of 120 m, while for the rest, the systematic error was more than 0.5 m. Smoothing the CHM during accounting leads to an increase in systematic error.

Table 6. Average height determination accuracy indicators using UAV data

CHM type	*RMSE, m*	*RMSE (%)*	*Bias, m*	*Bias (%)*
a80	1.00	7.98	-0.38	-2.99
a80SMTH	0.92	7.34	-0.49	-3.89
m80	0.78	6.23	-0.31	-2.50
m80SMTH	0.92	7.34	-0.49	-3.89
a120	0.84	6.72	-0.48	-3.79
a120SMTH	1.08	8.59	-0.73	-5.79
m120	1.07	8.52	-0.60	-4.79
m120SMTH	1.21	9.68	-0.71	-5.69
a150	1.01	8.04	-0.75	-5.99
a150SMTH	1.03	8.26	-0.75	-5.99
m150	0.95	7.57	-0.63	-4.99
m150SMTH	0.95	7.57	-0.63	-4.99

Source: compiled by the author

The area-based approach to forest management requires a correct inventory of tree stands. That is why the use of photogrammetry technology is promising in comparison with more expensive technologies. Identification of top trees in a stand based on CHM is quite simple and does not require significant computing power (Ferraz *et al.*, 2012).

The studies (Popescu & Wynne, 2004; Ottoy *et al.*, 2022) showed that to individual tree detection in plantations with different stand parameters, it is necessary to establish the dependence of crown radius on tree height. In contrast to previous publications, confidence interval parameters around the established regression of crown radius on tree height were used to avoid missing treetops. Thus, we used confidence intervals at the level of 2.5% of the established regression relationship to reduce the parameters of the treetop filtering function.

In the present study, no significant advantages were found in applying a smoothing filter to the canopy height model, as reported by Mohan *et al.* (2017). However, differences in the results obtained may depend on the input materials used, the CHM resolution, or the characteristics of the studied forest stands. It has been established that the quality of remote-sensing input images has the greatest impact on errors in tree detection. For example, the study by J. Torres-Sánchez *et al.* (2018) shows that the best detecting results are obtained with the maximum degree of image overlap.

The confusion matrix data was used, which makes it possible to assess which errors deteriorate the individual tree detecting performance. Problems with the identification of trees less than 2 m in height that grew on the site of natural origin were identified. For studies of low stands, it is necessary to use data from a lower altitude than was used in our article and greater spatial resolution (Lin *et al.*, 2023). A. Bilous *et al.* (2021) indicate that the results of measuring the height of Scot's pine trees in mature stands using CHM data are more accurate than using handheld height clinometers.

As the spatial resolution of the remote sensing data changes, the mean square error for the determined average stand height does not differ significantly, as confirmed by S. Kameyama & K. Sugiura (2021). However, it was found that a decrease in the spatial resolution of the input remote sensing data leads to an increase in errors in measuring the height of individual trees. If we evaluate the *Bias* value for the determined average heights, we still observe the same tendency to underestimate them. Heights were underestimated for natural stands that had not formed a forest stand, and the effect of underestimating heights by remote sensing was also observed in the study of L. Lin *et al.* (2023) on low trees.

Errors of tree height estimating also depend on the errors in the digital elevation model. This is especially important in areas with closed stands where the ground surface is difficult to see, as well as in areas with complex terrain. Therefore, it is important to use the most accurate digital elevation models for establishing the stands parametes.

Conclusions

Based on the results of the study, it was found that remote sensing data with higher spatial resolution according to several criteria are best suited for determining pine stand parameters.

Based on the survey data from altitude of 80 m (spatial resolution of 2.2 cm/pix), the smallest errors in determining the height and detecting the treetops were obtained. The *F-score* for the quality of individual treetop detection was in the range of 0.77-0.78. The Bias error in measuring the height of individual trees ranged from -0.14 to -0.31 m, and the average height of the stand was from -0.31 to -0.49 m.

Based on the data from the 120 m survey (3.3 cm/pix), the results were close to the previous ones. The use of a soft degree of filtering when building a point cloud leads to false discovery treetops. The *F-score* was in the range of 0.75-0.77. The *bias* for measuring the height of individual trees ranged from -0.21 to -0.47 m, with the average height from -0.48 to -0.73 m (the smallest systematic error when using a point cloud with aggressive filtering and without CHM filtering).

The worst results were obtained for data taken from altitude of 150 m (4.1 cm/pix). The *F-score* values deteriorate to 0.68-0.70. The systematic error in determining the height of individual trees increases (*Bias* ranges from -0.56 to -1.02 m), and the average stand height from -0.63 to -0.75 m. In this case, the highest systematic error rates are for CHM with aggressive filtering.

It has been established that for forestry research, it is necessary to collect remote sensing data with a longitudinal image overlap of at least 90%. Reducing the spatial resolution of the input images to 4 cm/pix worsens the results of terrain surface classification and DEM creation.

The results of the study indicate that the quality of detecting individual Scots pines and determining their heights depends on the parameters of UAV data collection. The results obtained should be considered when planning the collection of optical data from UAVs in future studies, in particular, their potential impact on the accuracy of determining a wider range of stand parameters. Similar studies may be required to establish optimal parameters for collecting optical data in deciduous stands (on the territory of Ukraine). Errors in detecting and determining the heights of low trees indicate the need to find optimal parameters for UAV data collection separately for forest plantations and young stands.

Conflict of Interest

The author declares no conflict of interest.

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References

[1] Bilous, A.M., Diachuk, P.P., Zadorozhniuk, R.M., Matsala, M.S., & Burianchuk, M.M. (2021). Accuracy of selected methods of measurement of tree heights. *Ukrainian Journal of Forest and Wood Science*, 12(1), 6-16. doi: 10.31548/forest2021.01.001.

[2] Duncanson, L.I., Cook, B.D., Hurtt, G.C., & Dubayah, R.O. (2014). An efficient, multi-layered crown delineation algorithm for mapping individual tree structure across multiple ecosystems. *Remote Sensing of Environment*, 154, 378-386. doi: 10.1016/j.rse.2013.07.044.

[3] Ferraz, A., Bretar, F., Jacquemoud, S., Gonçalves, G., Pereira, L., Tomé, M., & Soares, P. (2012). 3-D mapping of a multi-layered Mediterranean forest using ALS data. *Remote Sensing of Environment*, 121, 210-223. doi: 10.1016/j.rse.2012.01.020.

[4] Graham, A.N.V., Coops, N.C., Tompalski, P., Plowright, A., & Wilcox, M. (2020). Effect of ground surface interpolation methods on the accuracy of forest attribute modelling using unmanned aerial systems-based digital aerial photogrammetry. *International Journal of Remote Sensing*, 41(9), 3287-3306. doi: 10.1080/01431161.2019.1694722.

[5] Guimarães, N., Pádua, L., Marques, P., Silva, N., Peres, E., & Sousa, J.J. (2020). Forestry remote sensing from unmanned aerial vehicles: A review focusing on the data, processing and potentialities. *Remote Sensing*, 12(6), article number 1046. doi: 10.3390/rs12061046.

[6] Heurich, M. (2008). Automatic recognition and measurement of single trees based on data from airborne laser scanning over the richly structured natural forests of the Bavarian Forest National Park. *Forest Ecology and Management*, 255(7), 241-2433. doi: 10.1016/j.foreco.2008.01.022.

[7] Holiaka, D., Kato, H., Yoschenko, V., Onda, Y., Igarashi, Y., Nanba, K., Diachuk, P., Holiaka, M., Zadorozhniuk, R., Kashparov, V., & Chyzhevskyi, I. (2021). Scots pine stands biomass assessment using 3D data from unmanned aerial vehicle imagery in the Chernobyl Exclusion Zone. *Journal of Environmental Management*, 295, article number 113319. doi: 10.1016/j.jenvman.2021.113319.

[8] Kameyama, S., & Sugiura, K. (2021). Effects of differences in structure from motion software on image processing of unmanned aerial vehicle photography and estimation of crown area and tree height in forests. *Remote Sensing*, 13(4), article number 626. doi: 10.3390/rs13040626.

[9] Korpela, I. (2004). *Individual tree measurements by means of digital aerial photogrammetry*. Tampere: The Finnish Society. of Forest Science. doi: 10.14214/sf.sfm3.

[10] Lin, L., Hao, Z., Post, C. J., & Mikhailova, E. A. (2023). Protection of coastal shelter forests using UAVs: Individual tree and tree-height detection in *Casuarina equisetifolia* L. forests. *Forests*, 14(2), article number 233. doi: 10.3390/f14020233.

[11] Ma, K., Chen, Z., Fu, L., Tian, W., Jiang, F., Yi, J., Du, Z., & Sun, H. (2022). Performance and sensitivity of individual tree segmentation methods for UAV-LiDAR in multiple forest types. *Remote Sensing*, 14(2), article number 298. doi: 10.3390/rs14020298.

[12] Maxwell, A.E., Warner, T.A., & Guillén, L.A. (2021). Accuracy assessment in convolutional neural network-based deep learning remote sensing studies – Part 1: Literature review. *Remote Sensing,* 13(13), article number 2450. doi: 10.3390/rs13132450.

[13] McRoberts, R.E., & Tomppo, E. (2007). Remote sensing support for national forest inventories. *Remote Sensing of Environment*, 110(4), 412-419. doi: 10.1016/j.rse.2006.09.034.

[14] Mensuration description of forest land plots, Kyiv region, State Specialized Enterprise "Pivnichna Pushcha", Paryshiv forestry (2017). Irpin: Ukrainian State Project Forest Management Production Association VO "Ukrderzhlisproekt".

[15] Mohan, M., Leite, R.V., Broadbent, E.N., Wan Mohd Jaafar, W.S., Srinivasan, S., Bajaj, S., Dalla Corte, A.P., do Amaral, C.H., Gopan, G., Saad, S.N.M., Muhmad Kamarulzaman, A.M., Prata, G.A., Llewelyn, E., Johnson, D.J., Doaemo, W., Bohlman, S., Almeyda Zambrano, A.M., & Cardil, A. (2021). Individual tree detection using UAV-lidar and UAV-SfM data: A tutorial for beginners. *Open Geosciences*, 13(1), 1028-1039. doi: 10.1515/geo-2020-0290.

[16] Mohan, M., Silva, C., Klauberg, C., Jat, P., Catts, G., Cardil, A., Hudak, A., & Dia, M. (2017). Individual tree detection from unmanned aerial vehicle (UAV) derived canopy height model in an open canopy mixed conifer forest. *Forests*, 8(9), article number 340. doi: 10.3390/f8090340.

[17] Myroniuk, V., Bell, D.M., Gregory, M.J., Vasylyshyn, R., & Bilous, A. (2022). Uncovering forest dynamics using historical forest inventory data and Landsat time series. *Forest Ecology and Management*, 513, article number 120184. doi: 10.1016/j.foreco.2022.120184.

[18] Ota, T., Ogawa, M., Mizoue, N., Fukumoto, K., & Yoshida, S. (2017). Forest structure estimation from a UAV-based photogrammetric point cloud in managed temperate coniferous forests. *Forests*, 8(9), article number 343. doi: 10.3390/f8090343.

[19] Ottoy, S., Tziolas, N., Van Meerbeek, K., Aravidis, I., Tilkin, S., Sismanis, M., Stavrakoudis, D., Gitas, I. Z., Zalidis, G., & De Vocht, A. (2022). Effects of flight and smoothing parameters on the detection of taxus and olive trees with UAV-borne imagery. *Drones*, 6(8), article number 197. doi: 10.3390/drones6080197.

[20] Pádua, L., Vanko, J., Hruška, J., Adão, T., Sousa, J.J., Peres, E., & Morais, R. (2017). UAS, sensors, and data processing in agroforestry: A review towards practical applications. *International Journal of Remote Sensing,* 38(8-10). doi: 10.1080/01431161.2017.1297548.

[21] Plowright, A. (2020). Canopy analysis in R using Forest Tools. Retrieved from https://cran.r-project.org/web/packages/ForestTools/vignettes/treetop_analysis.html.

[22] Popescu, S.C., & Wynne, R.H. (2004). Seeing the trees in the forest. *Photogrammetric Engineering & Remote Sensing*, 70(5), 589-604. doi: 10.14358/PERS.70.5.589.

[23] Silva, C.A., Hudak, A.T., Vierling, L.A., Valbuena, R., Cardil, A., Mohan, M., Almeida, D.R.A., Broadbent, E.N., Almeyda Zambrano, A.M., Wilkinson, B., Sharma, A., Drake, J.B., Medley, P.B., Vogel, J.G., Prata, G.A., Atkins, J.W., Hamamura, C., Johnson, D.J., & Klauberg, C. (2022). TREETOP: A Shiny-based application and R package for extracting forest information from LIDAR data for ecologists and conservationists. *Methods in Ecology and Evolution*, 13(6), 1164-1176. doi: 10.1111/2041-210X.13830.

[24] Stereńczak, K., Kraszewski, B., Mielcarek, M., Piasecka, Ż., Lisiewicz, M., & Heurich, M. (2020). Mapping individual trees with airborne laser scanning data in an European lowland forest using a self-calibration algorithm. *International Journal of Applied Earth Observation and Geoinformation*, 93, article number 102191. doi: 10.1016/j.jag.2020.102191.

[25] Su, H., Shen, W., Wang, J., Ali, A., & Li, M. (2020). Machine learning and geostatistical approaches for estimating aboveground biomass in Chinese subtropical forests. *Forest Ecosystems*, 7(1), article number 64. doi: 10.1186/s40663-020-00276-7.

[26] Torres-Sánchez, J., López-Granados, F., Borra-Serrano, I., & Peña, J.M. (2018). Assessing UAV-collected image overlap influence on computation time and digital surface model accuracy in olive orchards. *Precision Agriculture*, 19(1), 115-133. doi: 10.1007/s11119-017-9502-0.

[27] Westoby, M.J., Brasington, J., Glasser, N.F., Hambrey, M.J., & Reynolds, J.M. (2012). 'Structure-from-Motion' photogrammetry: A low-cost, effective tool for geoscience applications. *Geomorphology*, 179, 300-314. doi: 10.1016/j.geomorph.2012.08.021.

[28] White, J.C., Coops, N.C., Wulder, M.A., Vastaranta, M., Hilker, T., & Tompalski, P. (2016). Remote sensing technologies for enhancing forest inventories: A review. *Canadian Journal of Remote Sensing*, 42(5), 619-641. doi: 10.1080/07038992.2016.1207484.

Вплив параметрів збору даних з БПЛА на встановлення таксаційних показників соснових деревостанів

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Анотація. Широкий спектр систем БПЛА, що застосовуються для досліджень лісів, потребують уніфікації підходів до збору даних Метою дослідження було визначення оптимальних параметрів збору даних з БПЛА для отримання точної інформації про деревостани з урахуванням витрат ресурсів на її збір. Процес збору даних дистанційної зйомки складався з дев'яти комбінацій, що розділені на три рівні перекриття та три рівні просторового розрізнення (висоти зйомки), та зміною ступеня фільтрації щільної хмари точок під час обробки зображень. Дешифрування дерев у деревостані виконано із застосуванням мови програмування R та пакету «ForestTools». Використано результати оцінювання залежності радіусу крон дерев від їхньої висоти для встановлення параметрів функції змінного фільтру пошуку локальних максимумів для деревостанів сосни звичайної. Похибки ідентифікації верхівок оцінювались із застосуванням показнику F–score. Встановлені висоти порівнювались з польовими даними наземної таксації. Частка класифікованого рельєфу у щільній хмарі точок зменшувалась від загальної площі полігону з використанням зображень просторового розрізнення 4,1 см/пікс (висота зйомки 150 м). У роботі представлено результати оцінювання впливу просторового розрізнення оптичних зображень зібраних з БПЛА та їхнього перекриття на результати визначення таксаційних показників деревостанів. Визначено, що фотограмметричну зйомку з вхідними зображеннями з повздовжнім перекриттям меншим 90 % не доцільно застосувати для дослідження лісових ділянок за рахунок неможливості вирівнювання всіх зображень. Результати оцінки обліку дерев у деревостані показали, що найбільш доцільно застосовувати зображення із просторовим розрізненням до 3,3 см/пікс (висота зйомки 120 м), в іншому випадку збільшується частка пропущених верхівок дерев. Зменшення просторового розрізнення даних дистанційної зйомки призводить до збільшення похибок у визначенні висоти окремих дерев, встановлені середні висоти дослідних ділянок мали таку ж тенденцію. Зважаючи на сукупність оцінених факторів застосування зображень із просторовим розрізненням понад 3,3 см/пікс не рекомендовано використовувати для досліджень лісових насаджень у зв'язку зі збільшення похибок дешифрування верхівок та встановлення висоти дерев. Отримані результати можна застосовувати для підбору параметрів збору даних під час досліджень деревостанів сосни звичайної, зокрема для оцінки показників їхнього запасу та фітомаси

Ключові слова: фотограмметрія; цифрова модель навісу; дешифрування; визначення висоти; цифрова модель рельєфу

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Mountain recreation impact on changes in soil penetration resistance of spruce forests

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Abstract. The uniqueness of the Carpathian Mountain Forest ecosystems, a large part of which belongs to nature conservation areas, attracts a significant number of visitors annually. Intensive tourist flow on popular hiking trails leads to recreational digression, topsoil compaction, development of erosion processes and deterioration of forests. The research aims to determine the impact of recreation as an external mechanical impact on soil compaction by determining the soil penetration resistance under the canopy of predominant spruce stands. For this purpose, soil penetration resistance was measured with a penetrometer along two hiking trails within the root layer of the soil at four measuring sites at different distances from the hiking trail. In general, under the canopy of a forest stand, the soil cover is not homogeneous and the obtained penetration resistance values are characterised by considerable variability. It was revealed that for the "Zelene village – Uhorski skeli rocks" hiking trail in the areas close to the path (up to 20 m) there is a significant increase in soil penetration resistance compared to remote areas: at a depth of 10 cm it

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doubles, at a depth of 20 cm – by 20-40%, but with further deepening, the penetration resistance level off. At the same time, for the more popular "To Mount Pip Ivan Chornohirskyi" hiking trail, in the area adjacent to the trailbed, the penetration resistance reaches 19.6 kg·cm^{-2} in the upper 10 cm layer, and at a depth of 30 cm, it peaks at 37.8 kg·cm^{-2} (over 3 MPa), which affects the root spatial distribution of spruce forests. Intensive erosion processes due to soil compaction with an increase in soil penetration resistance above 60 kg·cm^{-2} (~6 MPa) are observed on the trailbed. The practical significance of the results obtained, and the established patterns is to complement existing methods for assessing the degree of recreational digression in mountainous conditions and can be the basis for designing measures to regulate tourist flows and restore affected areas

Keywords: soil compaction; digression; hiking trail; penetrometer; ecosystem

Introduction

Mountain ecosystems are the most valuable in Europe by species richness and ecological importance (14.8% of the Carpathians are in Ukraine), which requires nature conservation areas establishment on territory. At the same time, the preserved uniqueness of mountain ecosystems compared to commercial forests attracts visitors, and the number of visitors is constantly growing (State Statistics..., 2021). According to the terms of use of protected areas (The Law of Ukraine..., 1992), recreation requires compliance with the protection plans of protected natural complexes and a differentiated approach according to functional zoning. In the area of regulated or stationary recreation, any activity that may lead to environmental degradation and decrease the recreational value of the territory of the national nature park is prohibited.

The Carpathian region is characterised by various types of tourism, including mountain tourism (hiking), skiing, cycling, natural history, equestrian, cultural, recreational, and health tourism, etc. C. Pickering *et al.* (2010) concluded that equestrian tourism, jeeping and cycling, and off-road rallies cause the most damage on hiking trails. These impacts include soil degradation, changes in vegetation cover, reduction of biodiversity, fragmentation of forests, and concentration and development of tourist infrastructure. For mass tourism in mountain national parks, there are problems with regulation and compliance with the rules of stay in protected areas, which are slow to recover to ecological balance. In general, the most significant negative impacts on mountain ecosystems occur when tourism is uncontrolled.

The mismatch between demand, the existing functional zoning and the recreational capacity of the Carpathian territories affects natural communities due to the excessive concentration of visitors in the most popular tourist destinations. As a result, a high degree of recreational degradation is observed in some areas, which is primarily reflected in the deterioration of the soil condition and physical properties and leads to irreversible changes in the vegetation cover. J. Toivio *et al.* (2017) found that disturbed soil fosters to decrease in the forest ecosystems productivity, which leads to the loss of ecosystem services, especially regulating, supporting and resource provisioning. Forest soils have lower strength and lower bulk density compared to soils of open areas (pastures), which makes them more sensitive to external mechanical stresses (Blanco-Canqui *et al.*, 2005; Bormann & Klaassen, 2008). X. Hao *et al.* (2008) noted that the assessment of soil changes under anthropogenic impact is based on soil penetration resistance, density, and porosity. Even slight compaction can affect important ecosystem processes and lead to the deterioration of soil chemical and/or physical properties (Ampoorter *et al.*, 2007; S. Yao *et al.*, 2015). D. Sinnett *et al.* (2008) found that soil compaction leads to reduced porosity, reduced nutrient mineralisation rates, modified structure, and thus impeded root development. The processes of soil compaction have a cumulative effect. Long-term soil compaction affects not only aeration but also changes soil moisture regime. D. Jordan *et al.* (2003) stated that under significant mechanical stress, the growth rate and penetration capacity of roots decrease, which leads to a decrease in the rate of water and nutrient absorption.

External mechanical impact on the soil increases its penetration resistance (Frey *et al.*, 2011; Cambi *et al.*, 2016). Soil penetration resistance is a physical property of soil that depends on its bulk density, texture (Imhoff *et al.*, 2016), moisture content (Junior *et al.*, 2014), porosity (Holthusen *et al.*, 2018), structural particle size, pH, mineral and organic content. The study of soil penetration resistance due to external mechanical impact is important for assessing recreational load (Budakova *et al.*, 2021).

The Carpathian National Nature Park (CNNP) is characterised by forest ecosystems represented mainly by spruce stands (Kravchynskyi *et al.*, 2018). The ecological resilience of spruce forests is declining and is associated with significant sensitivity to global climate change (Lavnyi & Pelukh, 2019), and the development of tourism activities in the region add pressure on forest ecosystems. As a result of high recreational impact, the above-ground vegetation is disturbed, and the upper soil layers containing the root system of European spruce are compacted and destroyed (Brusak & Malets, 2018). Following N.V. Yorkina *et al.* (2020), the stage of recreational degradation in forest natural complexes is determined based on a description of the state of the grass and moss cover, forest litter, tree stand, understorey, and the recreation coefficient. The work of V. Brusak (2018) allows to estimate the recreational digression of the micro terrain of hiking trails by the volume of material removed from 1 m^2 of the trailbed. However, the study of the impact of recreational activities on changes in the physical properties of the root-contained soil layer is not complete.

The research aims to assess changes in the soil penetration resistance of spruce stands in the Carpathians, caused by external mechanical stresses from recreational impacts.

Materials and Methods

Sample plots are in forest stands within the Ivano-Frankivsk region (Fig. 1), which represents the main part of the Ukrainian Carpathians. More than 40% of the Carpathian region is covered by forests and 24% of the region's mountain forests are classified as nature reserve fund of Ukraine (Kiseliuk *et al*. 2009).

Spruce forests occupy 79% of the Carpathian NNP forests and 73% of them are natural. Four sample plots were established at an altitude between 1030 m and 1095 m a.s.l. within the pure spruce high-altitude vegetation belt. The coordinates and characteristics of the study plots are given in Table 1.

To assess the degree of impact of recreational activity on the territory of the Carpathian NNP and adjacent tourist sites, the soil penetration resistance values along two hiking trails were measured and analysed. Penetration resistance measurements were carried out using a LAN-M PRO penetrometer (Ukraine). This is the most common approach for assessing the soil penetration resistance (Dexter *et al.*, 2007). The LAN-M PRO penetrometer provides soil penetration resistance measurements every 2.5 cm soil profile depth. Soil penetration resistance was measured in the upper 40 cm soil layer, due to the peculiarities of the stands root systems distribution under the canopy in which the measurements were conducted. All data were collected throughout September 2021 for all studied stands. Soil penetration resistance was determined along two trails: "Zelene village – Uhorski skeli rocks" (SP1, SP2, SP3) and "To Mount Pip Ivan Chornohirskyi" (SP4). The penetration resistance measurements were taken with a gradual remoteness from the trail line away into the forest ecosystems (Fig. 2). Thus, the sample plot SP4 is located adjoint to the "To Mount Pip Ivan Chornohirskyi" hiking trail (5 m from the centre). For the "Zelene village – Uhorski skeli rocks" hiking trail, 3 temporal sample plots were established, including SP1 (5 m from the centre) adjacent to the trail line, and SP3 (40 m from the centre) and SP2 (20 m from the centre) located deep in the forest.

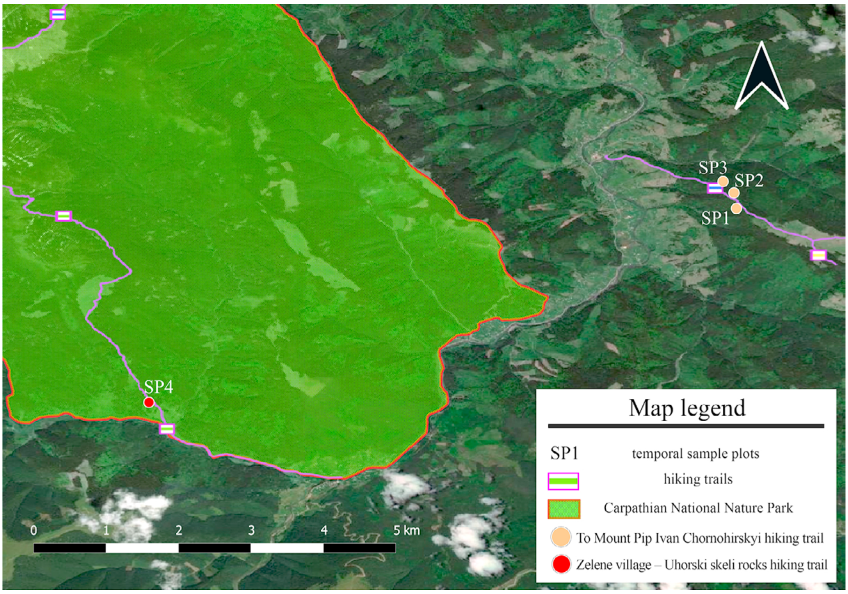

Figure 1. Location of sample plots on hiking trails

Source: compiled by the authors based on QGIS geoinformation system

Table 1. General characteristics of the sample plots in spruce stands

TSP	Altitude, m a.s.l.	Distance to trail	Coordinates	Slope steepness, deg.	Slope exposure	Age, years	Dominant species (%)	Site index	Mean height, m	Mean diameter, cm
"Zelene village – Uhorski skeli rocks" hiking trail										
SP1	1095	5	48.041077°N 24.776265°E	<2	South-West	48	80% NS-B	I^b	25.4	32.4
SP2	1090	20	48.041410°N 24.776077°E	<2	North-East	67	93% NS-B	I^a	26.4	28.3

Table 1, Continued

TSP	Altitude, m a.s.l.	Distance to trail	Coordinates	Slope steepness, deg.	Slope exposure	Age, years	Dominant species (%)	Site index	Mean height, m	Mean diameter, cm
SP3	1040	40	48.043020°N 24.773406°E	8	North-East	62	86% NS-B	I[a]	24.9	26.7
"To Mount Pip Ivan Chornohirskyi" hiking trail										
SP4	1030	5	48.004258°N 24.668548°E	18	South	58	100% NS	I[b]	29.3	31.5

Note: TSP – temporal sample plot; sample plots SP1-3 along the "Zelene village – Uhorski skeli rocks" hiking trail, sample plot SP4 is located along the "To Mount Pip Ivan Chornohirskyi" hiking trail; NS – Norway spruce; NS-B – Norway spruce with admixture of European beech
Source: compiled by the authors

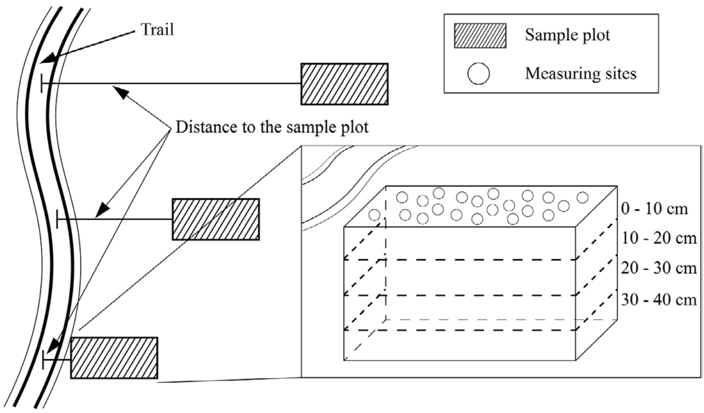

Figure 2. Schematic representation of the experiment setup on the route "Zelene village – Uhorski skeli rocks" hiking trail
Source: compiled by the authors based on QGIS geoinformation system

Penetration resistance measurements on each sample plot were made in 20 replicates, with each measurement made at a distance of at least 1 m from the nearest tree. Abnormally high or low values were not considered in further analysis. In addition, penetration resistance measurements were made in 5 replicates on the trailbeds, opposite to the sample plots. FIELD-M Archive Viewer 2.3 was used to visualise the extrapolated soil penetration resistance values within the sample plots. Differences between soil penetration resistance values at different depths within each sample plot were determined using One-way ANOVA followed by Tukey's HSD post hoc test. Two-Way ANOVA and Tukey's HSD were used to compare the penetration resistance values at different depths along the two trails. All statistical analyses were performed using the R software (Version 4.0.2) (The R Project..., n.d.). The following packages were used to analyse and graphically interpret the results: "psych", "ggplot2", and "ggppubr".

Results and Discussion

The obtained penetration resistance values for all sample plots are highly variable. A brief description of the soil penetration resistance for the sample test SP1 on the “Zelene village – Uhorski skeli rocks” hiking trail is shown in Table 2. This plot is characterised by an increase in soil penetration resistance up to a depth of 22.5 cm from 0.3 to 25.5 kg·cm^{-2}. With the further immersion of the penetrometer in the soil up 40 cm depth, the values levelled off and the mean value ranged from 12.7 to 15.5 kg·cm^{-2}. Similar results were obtained by Budakova *et al.* (2021), where soil penetration resistance values increased significantly up to a depth of 25-30 cm.

Table 2. Descriptive statistics of soil penetration resistance values on the “Zelene village – Uhorski skeli rocks” hiking trail (SP1)

Depth, cm	Descriptive statistics					
	Mean penetration resistance, kg·cm^{-2}	Median	sd – standard deviation	se – standard error	Skewness	Kurtosis
0	2.1	2	1.38	0.31	0.39	-1
2.5	4.7	4.6	1.82	0.41	-0.21	-0.6
5	8	8.1	2.23	0.5	0.09	-0.99
7.5	9.7	10.1	3.04	0.68	-1.06	1.6
10	12	12.2	2.28	0.51	-0.03	-1.03
12.5	14.6	14.2	2.98	0.67	0.22	-1
15	14	14	2.36	0.53	0.18	-0.67
17.5	14.3	14	3.5	0.78	0.19	-1.18
20	16.4	17.1	2.94	0.66	-0.25	-1.34
22.5	19.8	20.9	3.83	0.86	-0.04	-1.66
25	19	16.8	4.21	0.94	0.56	-1.19
27.5	15.3	15.4	2.23	0.51	-0.16	-0.43
30	15.3	15.5	2.26	0.53	0.45	0.38
32.5	15.5	15.6	2.08	0.5	-0.53	-0.25
35	12.7	12.8	2.95	0.72	-0.33	-0.03
37.5	15.4	16	2.05	0.5	-0.4	-1.26
40	14.7	14.1	1.49	0.36	0.64	-0.61

Source: compiled by the authors

The graphical interpretation of soil penetration resistance values distribution on the sample plot SP1 on the “Zelene village – Uhorski skeli rocks” hiking trail is shown in Figure 3.

The results of a one-way ANOVA indicate a statistically significant difference between the mean values of soil penetration resistance ($p<0.05$) for different categories of soil depth. Up to a depth of 20 cm, which is characterised by the highest rates of soil root distribution in spruce forests (Yukhnovskyi *et al.*, 2020), there is a sharp increase in soil penetration resistance, and at a depth of 30-40 cm, there is a gradual decrease. The results of the post hoc Tukey’s HSD test indicate that the mean values of penetration resistance at a depth of 10-20 and 30-40 cm are similar ($p=0.986$). Thus, the sample plot SP1 is exposed to the highest external impact due to its location. Therefore, the presence of forest litter, vegetation cover, and topsoil are crucial for preventing the erosion processes development (Zuazo & Pleguezuelo, 2008). Following (Zhukov *et al.*, 2021), topography and stand characteristics can explain 30-50% of the spatial variation in soil penetration resistance.

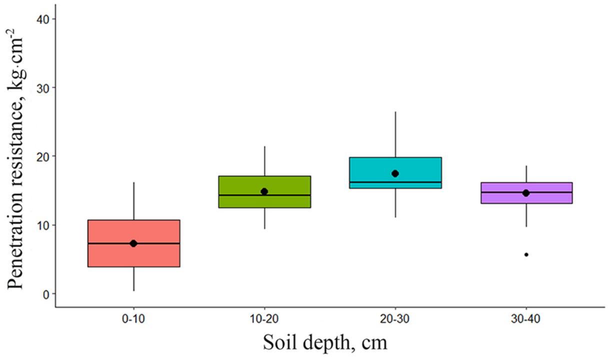

Figure 3. Distribution of soil penetration resistance with depth on the sample plot SP1 on the “Zelene village – Uhorski skeli rocks” hiking trail

Source: compiled by the authors

With 20 m distance from the “Zelene village – Uhorski skeli rocks” hiking trail, sample plot SP2 was surveyed (Table 3).

Similarly, to the SP1, which is directly adjacent to the hiking trail, a trend towards an increase in penetration resistance with depth is observed at a distance of 20 m from the trail. The lowest soil penetration resistance values (1.3 kg·cm^{-2}) were observed in the upper layer at a depth of 5 cm, and the maximum mean value was at a depth of 25 cm, with the further immersion of the penetrometer, the values gradually decrease, i.e., the compaction of the soil decreases. A graphical representation of the soil penetration resistance values distribution at SP2 on the “Zelene village – Uhorski skeli rocks” hiking trail is shown in Figure 4.

Table 3. Descriptive statistics of soil penetration resistance values on the “Zelene village – Uhorski skeli rocks” hiking trail (SP2)

Depth, cm	Descriptive statistics					
	Mean penetration resistance, kg·cm^{-2}	Median	sd – standard deviation	se – standard error	Skewness	Kurtosis
0	2.6	2.6	0.91	0.25	0.66	-0.02
2.5	3.7	3.9	0.9	0.25	-0.43	-0.9
5	6.6	6.7	1.34	0.37	-0.13	-0.97
7.5	9.2	10.1	2.16	0.6	-0.66	-0.92
10	12	12.4	2.59	0.72	-0.17	-1.1
12.5	13.6	13	3.74	1.04	0.09	-1.68
15	14.6	14.7	4.14	1.15	-0.36	-1.42
17.5	14.7	17.1	4.82	1.34	-0.46	-1.4
20	14.3	14.8	3.38	1.07	0.13	-1.41
22.5	16.8	16.8	4.33	1.37	0.09	-1.58
25	18.1	18.1	4.82	1.52	0.01	-1.8
27.5	17.6	17.3	5.24	1.66	0.08	-1.55
30	16.8	16.2	5.33	1.69	0.63	-1.13
32.5	15.3	14	5.47	1.73	0.9	-0.75

Table 3, Continued

Depth, cm	Descriptive statistics					
	Mean penetration resistance, kg·cm^{-2}	Median	sd – standard deviation	se – standard error	Skewness	Kurtosis
35	14.3	12.5	5.14	1.71	0.92	-0.8
37.5	13.4	11.9	4.58	1.53	1.03	-0.67
40	12.4	11.8	4.94	1.65	0.98	-0.2

Source: compiled by the authors

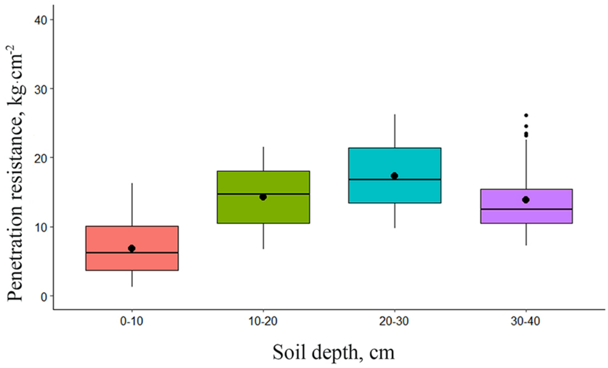

Figure 4. Distribution of soil penetration resistance with depth on the sample plot SP2 on the “Zelene village – Uhorski skeli rocks” hiking trail

Source: compiled by the authors

In general, for the sample plot SP2, there is a sharp increase in soil penetration resistance in the upper layers, which reaches its peak at a depth of 20-30 cm, followed by a gradual decrease at a depth of 30-40 cm. A statistically significant difference ($p<0.05$) was found between the mean values of penetration resistance for different categories of soil layer depths, and according to the results of Tukey’s HSD test, no significant differences ($p=0.977$) were found for soil layers 10-20 cm and 30-40 cm.

The most distant from “Zelene village – Uhorski skeli rocks” hiking trail is the SP3 plot. The results of the study of soil penetration resistance values at this site are presented in Table 4.

Table 4. Descriptive statistics of soil penetration resistance values on the “Zelene village – Uhorski skeli rocks” hiking trail (SP3)

Depth, cm	**Descriptive statistics**					
	Mean penetration resistance, kg·cm^{-2}	**Median**	**sd – standard deviation**	**se – standard error**	**Skewness**	**Kurtosis**
0	1.6	1.3	0.69	0.21	0.68	-0.8
2.5	2.6	2.5	0.99	0.31	0.31	-1.31
5	4	4.3	1.8	0.57	-0.06	-1.76
7.5	5.3	4.1	2.93	0.93	0.54	-1.52
10	6.6	6.2	4.24	1.36	0.28	-1.51
12.5	9.7	11	4.62	1.46	-0.65	-1.26

Table 4, Continued

Depth, cm	Descriptive statistics					
	Mean penetration resistance, kg·cm^{-2}	Median	sd – standard deviation	se – standard error	Skewness	Kurtosis
15	11.4	12.4	5.02	1.59	-0.63	-1.18
17.5	11.2	13.2	5.16	1.63	-0.32	-1.77
20	11.6	12.9	5.05	1.6	-0.33	-1.21
22.5	13.6	14	3.54	1.12	0.33	-0.21
25	15.2	15.7	3.57	1.13	-0.59	0.61
27.5	15.9	16.6	3.9	1.23	-1.33	1.37
30	15	15.6	4.11	1.3	-0.97	0.39
32.5	14.6	15.3	3.99	1.26	-0.27	-0.71
35	14.2	13.2	4.14	1.31	0.81	-0.18
37.5	15.8	16	4.3	1.36	0.32	-0.75
40	16.7	16.7	4.89	1.55	0.3	-1.3

Source: compiled by the authors

A gradual increase in the soil resistance to penetration is observed up to a depth of 27.5 cm and varies along the entire profile from 0.7 to 24.3 kg·cm^{-2}. The distribution of values by depth indicates the absence of a certain trend in the skewness. The distribution of penetration resistance values at SP3 on the "Zelene village – Uhorski skeli rocks" hiking trail is illustrated in Figure 5.

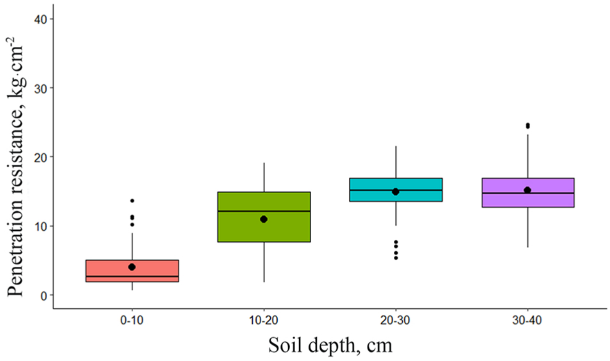

Figure 5. Distribution of soil penetration resistance with depth on the sample plot SP3 on "Zelene village – Uhorski skeli rocks" hiking trail
Source: compiled by the authors

The rapid increase in penetration resistance is observed only up to a depth of 20 cm and then the values have less variability with depth. The mean values of penetration resistance for different depth categories have a statistically significant difference ($p<0.05$) according to the results of One-way ANOVA, but with a depth of more than 20 cm, the mean values of penetration resistance do not differ significantly ($p=0.993$). That is, the soil structure is homogeneous with a gradual increase in its penetration resistance capacity.

The forest environment is extremely heterogeneous, including in the sample plot SP1 (Fig. 6), with the upper soil layers having a loose structure and low penetration resistance.

Under the influence of trees, the greatest variations in soil penetration resistance were observed compared to the influence of herbaceous vegetation (Kunakh *et al.*, 2022). Furthermore, the "Zelene village – Uhorski skeli rocks" hiking trail is also subject to periodic use of forestry vehicles. Forestry activities and recreational pressure accelerate the compaction of the soil and lead to a decrease in soil moisture, impaired infiltration, and reduced moisture available for plant growth (Deng *et al.*, 2003). The use of logging machines or illegal use of trucks on hiking trails has a significant impact on soil structure: overall soil porosity decreases by 20% and the number of macropores decreases by 50-60% (Teepe *et al.*, 2004). Importantly, according to S. Yaşar Korkanç (2014), 500 times of walking along the trail almost doubles the penetration resistance in its upper layer, from 3.78 kg·cm^{-2} to 6.06 kg·cm^{-2}.

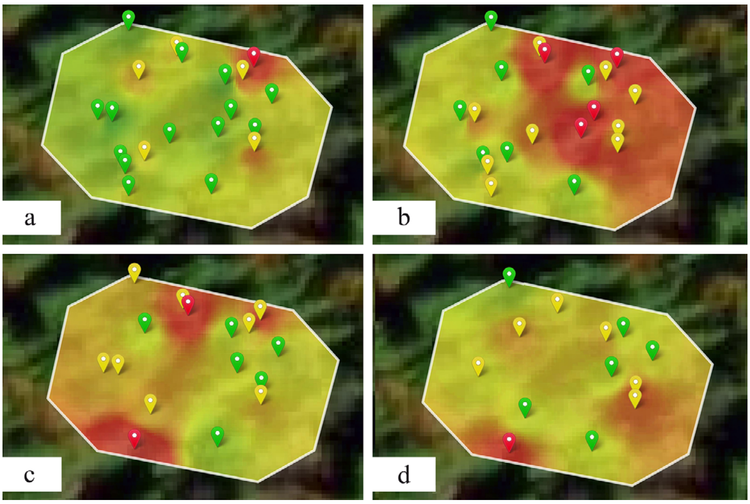

Figure 6. Extrapolated soil penetration resistance data at SP1 along the "Zelene village – Uhorski skeli rocks" hiking trail: a) 10 cm; b) 20 cm; c) 30 cm; d) 40 cm

Source: compiled by the authors

The sample plot SP4 is located along the "To Mount Pip Ivan Chornohirskyi" hiking trail in the Carpathian National Nature Park and under regular recreational use. According to the results of short-term monitoring, periodic illegal use of trucks for recreational purposes was recorded on this trail. The trail is characterised by significant soil layer erosion (up to 1 m relative to the level of undisturbed soil profile under the forest canopy), which causes inconvenience to tourists who use the trailside as a detour, thus disturbing the structure of the ground vegetation cover and forest litter. The central part of the tourist trails undergoes the greatest changes in the soil environment and vegetation condition. Due to the significant soil compaction, it was not possible to determine the penetration resistance values on the trailbed itself, as the topsoil compaction exceeded the maximum permissible values of the penetrometer (60 kg·cm^{-2} or 6 MPa). The penetration resistance of the soil was measured in the area adjacent to the edges of the trail (Table 5).

Table 5. Descriptive statistics of soil penetration resistance values on the "To Mount Pip Ivan Chornohirskyi" hiking trail (SP4)

Depth, cm	Descriptive statistics					
	Mean penetration resistance, kg·cm^{-2}	Median	sd – standard deviation	se – standard error	Skewness	Kurtosis
0	4.2	2.3	3.31	1.25	0.46	-1.78
2.5	10.1	10.4	3.68	1.36	-0.4	-1.03
5	15.2	16.4	4.03	1.52	-0.19	-1.79
7.5	16.6	16.2	2.07	0.78	-0.37	-1.47
10	19.7	17.9	5.24	1.98	0.39	-1.79
12.5	23	23.7	4.47	1.69	-0.4	-1.29
15	25.6	26.3	4.48	1.69	-0.06	-1.85
17.5	29.2	29.4	3.74	1.41	0.34	-1.42
20	30.9	31.6	6.25	2.36	0.1	-1.93
22.5	27	25.7	2.64	1	0.34	-1.92
25	25.4	25.5	0.96	0.36	0.01	-1.86
27.5	27.6	29.1	4.63	1.75	-0.02	-1.99
30	27.2	25.7	5.45	2.06	0.84	-0.73
32.5	27.8	29.6	3.99	1.51	-0.53	-1.73
35	28.2	29.3	3.6	1.36	-0.24	-1.51
37.5	29.9	31.3	5.17	1.95	-0.44	-1.6
40	26.5	27.4	2.62	0.99	-0.73	-1.19

Source: compiled by the authors

In the sample plot SP4, a sharp increase in the penetration resistance in the upper layers is present. The highest value was 37.8 kg·cm^{-2} at a depth of 30 cm. The summary results of soil penetration resistance are illustrated in Figure 7. The upper 0-10 cm layer has a wide range of values. At the depth of 10-20 cm, there is a significant soil compaction and an increase in the penetration resistance. One-way ANOVA showed no significant differences ($p>0.05$) for the resistance values at the depths of 10-20 cm, 20-30 cm, and 30-40 cm. Only the upper 0-10 cm layer had significantly lower penetration resistance values.

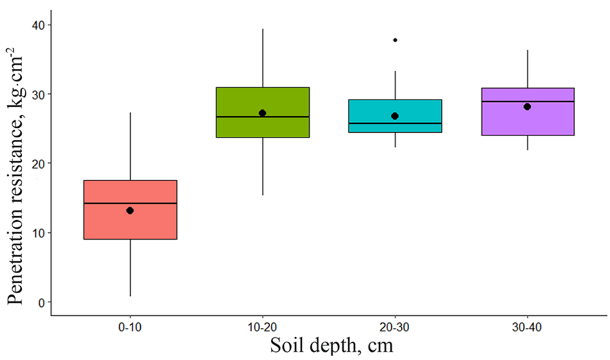

Figure 7. Distribution of soil penetration resistance indicators with depth on the sample plot SP4 on the "To Mount Pip Ivan Chornohirskyi" hiking trail

Source: compiled by the authors

Thus, all the studied sites under the spruce canopy are characterised by an increase in soil penetration resistance with depth. With a decrease in the distance to the trailbed the mean values of penetration resistance increase throughout the depth of the soil profile. Similar results on the trend of increasing soil penetration resistance while approaching the trail are reported by V.S. Budakova *et al.* (2021) for recreational facilities in the urban ecosystem. Moreover, J. Deng *et al.* (2003) determined that the closest areas to hiking trails are most affected by recreation in the Zhangjiajie National Forest Park in China.

Two-Way ANOVA and Tukey's HSD test were used to compare the penetration resistance values along the hiking trails at different depths. For the sample plots on the "Zelene village – Uhorski skeli rocks" hiking trail (SP1 and SP2), there was no statistically significant difference across the entire depth of the soil profile, despite the heterogeneity of the soil profile at SP1. The soil penetration resistance values in the top 20 cm layer were significantly different for SP1 and SP3, for SP3 and SP2 ($p<0.05$), which may indicate the presence of external mechanical impacts on the soil along the same trail. With increasing depth, the difference in penetration resistance is completely levelled. The soil penetration resistance along the popular "To Mount Pip Ivan Chornohirskyi" hiking trail (SP4) is significantly higher compared to the areas on the "Zelene village – Uhorski skeli rocks" hiking trail. The reasons for this are recreational use, soil erosion along the trail, illegal use of vehicles, and the lower thickness of the soil profile and bedrock outcrops. On the popular "Prypir-Zaroslyak" and "To Mount Hoverla" hiking trails, according to V. Brusak (2018) for the Carpathian NNP, at the final stage of topography transformation the disturbance of the soil cover (denuded surface) extends to a depth of 60 cm. According to this research, the volume of soil material washed from a trail segment can reach 0.5 m^3 per 1 m^2 and cause a catastrophic level of degradation.

According to (Sinnett *et al.*, 2008), soil penetration resistance in the range of 2 to 3 MPa (approximately 20-30 $kg{\cdot}cm^{-2}$) significantly impedes the development of root systems. Penetration resistance above 3 MPa causes a sharp decrease in the root distribution, as 70% of roots are formed in soil layers with a penetration resistance of less than 2 MPa and 90% of roots in soils with a penetration resistance of less than 3 MPa. The results obtained for the two hiking trails indicate significant fluctuations in soil penetration resistance. Along the "To Mount Pip Ivan Chornohirskyi" hiking trail, the penetration resistance values vary from 13.2 $kg{\cdot}cm^{-2}$ (~1.3 MPa) in the upper layers to 28.1 $kg{\cdot}cm^{-2}$ (~2.8 MPa) at depth. The compaction of surface soil layers due to recreational activities significantly impede the spread of European spruce root systems in mountain forest ecosystems. Penetration resistance values of more than 2 MPa mainly occur at a depth of more than 20 cm, where decrease in the European spruce root distribution was observed (Yukhnovskyi *et al.*, 2020).

The impact of soil compaction on its ability to function as a vital ecosystem has been studied in more detail than the duration of soil recovery processes. For soils, where forestry activities are performed , the predicted duration for the full recovery of the soil to its natural state can be 50-70 years (Mohieddinne *et al.*, 2019). The process of restoring soil cover in the upper layers (0-40 cm) can take decades, especially for areas disturbed by large vehicles, and without additional restoration treatments (Pousse *et al.*, 2022). According to (Goutal *et al.*, 2013; Bonnaud *et al.*, 2019), the processes of restoring the natural density and penetration resistance capacity of the soil are much faster than the restoration of water and air regimes. At the same time, the restoration of the upper soil layers to their natural state is faster compared to the deeper layers. The restoration of natural resistance is influenced by both physical factors and the activities of living organisms.

Conclusions

The forests of the Ukrainian Carpathians on the territory of the nature reserve fund, especially the National Nature Parks, are attractive objects for various types of tourism, including uncontrolled tourism. Conventional methods for assessing the impact of recreation on forest ecosystems are based on a description of the state of living ground cover, forest litter, tree stand, understory and undergrowth, and the recreation coefficient, but little regard for changes in the soil profile.

In mountainous conditions, active recreational activities cause soil compaction, which increases penetration resistance, reduces soil erosion resistance, and affects forest growth conditions. Soil compaction reduces porosity, which inhibits the development of European spruce root systems. Soil penetration resistance values of more than 3 MPa, which are limiting for root distribution, are observed in areas of forests adjacent to hiking trails and are characteristic of a depth of 10-20 cm. Directly on the hiking trails, there is a complete trampling of vegetation and forest litter, and erosion processes are developing, which is caused by significant soil compaction with a penetration resistance more than 60 kg·cm^{-2} (~6 MPa). In the studied areas, there is a heterogeneity of soil penetration resistance values, which is influenced by both environmental factors (occurrence of bedrock, activity of soil fauna, root systems, etc.) and anthropogenic factors (tourism, forestry machinery). Soil penetration resistance decreases by 20-40% with the distance from the hiking trails into the spruce forest. The decrease in penetration resistance indicates a decrease in external mechanical impact on the upper soil layers, living ground vegetation and root systems of trees.

The Ukrainian Carpathians have favourable conditions for ecotourism development, but sustainable development need to be promoted as well as careful use of recreational potential, and therefore comply with the regulations for visiting nature conservation areas.

The study of soil compaction processes creates the prerequisites for a regulatory assessment of the recreation impact and facilitates the scientific basis for planning measures to promote the restoration of the soil physical condition and restore forest ecosystems natural state.

Conflict of Interest

The authors declare no conflict of interest.

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References

[1] Ampoorter, E., Goris, R., Cornelis, W.M., & Verheyen, K. (2007). Impact of mechanized logging on compaction status of sandy forest soils. *Forest Ecology and Management*, 241(1-3), 162-174. doi: 10.1016/j.foreco.2007.01.019.

[2] Blanco-Canqui, H., Lal, R., Owens, L.B., Post, W.M., & Izaurralde, R.C. (2005). Strength properties and organic carbon of soils in the North Appalachian region. *Soil Science Society of America Journal*, 69, 663-673. doi: 10.2136/sssaj2004.0254.

[3] Bonnaud, P., Santenoise, Ph., Tisserand, D., Nourrisson, G., & Ranger, J. (2019). Impact of compaction on two sensitive forest soils in Lorraine (France) assessed by the changes occurring in the perched water table. *Forest Ecology and Management*, 437, 380-395. doi: 10.1016/j.foreco.2019.01.029.

[4] Bormann, H., & Klaassen, K. (2008). Seasonal and land use dependent variability of soil hydraulic and soil hydrological properties of two Northern German soils. *Geoderma*, 145, 295-302. doi: 10.1016/j.geoderma.2008.03.017.

[5] Brusak, V. (2018). Methodological aspects of the study of recreational digression of microrelief tourist's routes. *Problems of Geomorphology and Paleogeography of the Ukranian Carpathians and Adjacent Areas*, 1(8), 108-120.

[6] Brusak, V.P., & Malets, V.B. (2018). Recreational digression on tourist routes "On Hoverla mount" in Carpathian National Nature Park. In *Natural resources of the region: problems of use, revitalization and protection. Materials of the 3rd scientific seminar* (pp. 58-63). Lviv: Ivan Franko National University of Lviv.

[7] Budakova, V.S., Yorkina, N.V., Telyuk, P.M., Umerova, A.K., Kunakh, O.M., & Zhukov, O.V. (2021). Impact of recreational transformation of soil physical properties on micromolluscs in an urban park. *Biosystems Diversity*, 29(2), 78-87. doi: 10.15421/012111.

[8] Cambi, M., Certini, G., Fabiano, F., Foderi, C., Laschi, A., & Picchio, R., (2016a). Impact of wheeled and tracked tractors on soil physical properties in a mixed conifer stand. *IForest*, 9, 89-94. doi: 10.3832/ifor1382-008.

[9] Deng, J., Qiang, S., Walker, G.J., & Zhang, Y. (2003). Assessment on and perception of visitors' environmental impacts of nature tourism: A case study of Zhangjiajie National Forest Park, China. *Journal of Sustainable Tourism*, 11(6), 529-548. doi: 10.1080/09669580308667219.

[10] Dexter, A.R., Czyż, E.A., & Gaţe, O.P. (2007). A method for prediction of soil penetration resistance. *Soil and Tillage Research*, 93(2), 412-419. doi: 10.1016/j.still.2006.05.011.

[11] Frey, B., Niklaus, P.A., Kremer, J., Lüscher, P., & Zimmermann, S. (2011). Heavy-machinery traffc impacts methane emissions as well as methanogen abundance and community structure in oxic forest soils. *Applied and Environmental Microbiology*, 77, 6060-6068. doi: 10.1128/AEM.05206-11.

[12] Goutal, N., Renault, P., & Ranger, J. (2013). Forwarder traffic impacted over at least four years soil air composition of two forest soils in northeast France. *Geoderma*, 193-194, 29-40. doi: 10.1016/j.geoderma.2012.10.012.

[13] Hao, X., Ball, B.C., Culley, J.L.B., Carter, M.R., Parkin, G.W., Carter, M.R., & Gregorich, E.G. (2008). Soil density and porosity. In M.R. Carter, & E.G. Gregorich (Eds.), *Soil sampling and methods of analysis* (pp. 743-759). Manitoba: Canadian Society of Soil Science.

[14] Holthusen, D., Brandt, A.A., Reichert, J.M., & Horn, R. (2018). Soil porosity, permeability and static and dynamic strength parameters under native forest/grassland compared to no-tillage cropping. *Soil and Tillage Research*, 177, 113-124. doi: 10.1016/j.still.2017.12.003.

[15] Imhoff, S., Pires da Silva, A., Ghiberto, P.J., Tormena, C.A., Pilatti, M.A., & Libardi P.L. (2016). Physical quality indicators and mechanical behavior of agricultural soils of Argentina. *PLOS ONE*, 11(4), article number e0153827. doi: 10.1371/journal.pone.0153827.

[16] Jordan, D., Ponder, F.J., & Hubbard, V.C. (2003). Effects of soil compaction, forest leaf litter and nitrogen fertilizer on two oak species and microbial activity. *Applied Soil Ecology*, 23, 33-41. doi: 10.1016/S0929-1393(03)00003-9.

[17] Junior, D.D.V., Biachini, A., Valadão, F.C.A., & Rosa, R.P. (2014). Penetration resistance according to penetration rate, cone base size and different soil conditions. *Bragantia*, 73(2), 171-177. doi: 10.1590/brag.2014.013.

[18] Kiseliuk, O., Prykhodko, M., Yavorskyi, A., Abramiuk, Y., Belei, M., Belmeha, V., & Yaremen M. (2009). *Carpathian National Nature Park*. Ivano-Frankivsk: Foliant.

[19] Kravchynskyi, R.L., Motruk, M.V., & Stefurak, O.M. (2018). The reasons for the weakening of the biotic stability of spruce trees in the Carpathian National Park. In *Today's of the biological science* (pp. 135-136). Sumy: Sumy State Pedagogical University named after A.S. Makarenko.

[20] Kunakh, O., Zhukova, Y., Yakovenko, V., & Daniuk, O. (2022). Influence of plants on the spatial variability of soil penetration resistance. *Ekológia (Bratislava)*, 41(2), 113-125. doi: 10.2478/eko-2022-0012.

[21] Lavnyi, V., & Pelukh, O. (2019). Distribution and analysis of the state of secondary spruce stands in the Ukrainian Carpathians. *Proceedings of the Forestry Academy of Sciences of Ukraine*, 19, 60-67. doi: 10.15421/411927.

[22] Mohieddinne, H., Brasseur, B., Spicher, F., Gallet-Moron, E., Buridant, J., Kobaissi, A., & Horen, H. (2019). Physical recovery of forest soil after compaction by heavy machines, revealed by penetration resistance over multiple decades. *Forest Ecology and Management*, 449, article number 117472. doi: 10.1016/j.foreco.2019.117472.

[23] Pickering, C.M., Hill, W., Newsome, D., & Leung, Y.-F. (2010). Comparing hiking, mountain biking and horse riding impacts on vegetation and soils in Australia and the United States of America. *Journal of Environmental Management*, 91(3), 551-562. doi: 10.1016/j.jenvman.2009.09.025.

[24] Pousse, N., Bonnaud, P., Legout, A., Darboux, F., & Ranger, J. (2022). Forest soil penetration resistance following heavy traffic: A 10-year field study. *Soil Use and Management*, 38, 815-835. doi: 10.1111/sum.12730.

[25] Sinnett, D., Morgan, G., Williams, M., & Hutchings, T.R. (2008). Soil penetration resistance and tree root development. *Soil Use and Management*, 24(3), 273-280. doi: 10.1111/j.1475-2743.2008.00164.x.

[26] State Statistics Service of Ukraine (2021). *Tourism activities in Ukraine*. Retrieved from http://www.ukrstat.gov.ua/operativ/operativ2019/tyr/tyr_dil/arch_tyr_dil.htm.

[27] Teepe, R., Brumme, R., Beese, F., & Ludig, B. (2004). Nitrous oxide emission and methane consumption following compaction of forest soils. *Soil Science Society of America Journal,* 68, 605-611. doi: 10.2136/sssaj2004.6050.

[28] The Law of Ukraine No. 2456-XII "On the Nature Reserve Fund of Ukraine". (1992, June). Retrieved from https://zakon.rada.gov.ua/laws/show/2456-12#Text.

[29] The R Project for statistical computing. (n.d.). Retrieved from http://www.R-project.org/.

[30] Toivio, J., Helmisaari, H.S., Palviainen, M., Lindeman, H., Ala-Ilomäki, J., Sirén, M., & Uusitalo, J. (2017). Impacts of timber forwarding on physical properties of forest soils in southern Finland. *Forest Ecology and Management*, 405, 22-30. doi: 10.1016/j. foreco.2017.09.022.

[31] Yao, S., Teng, X., & Zhang, B. (2015). Effects of rice straw incorporation and tillage depth on soil puddlability and mechanical properties during rice growth period. *Soil and Tillage Research*, 146, 125-132. doi: 10.1016/j. still.2014.10.007.

[32] Yaşar Korkanç, S. (2014). Impacts of recreational human trampling on selected soil and vegetation properties of Aladag Natural Park, Turkey. *CATENA*, 113, 219-225. doi: 10.1016/j.catena.2013.08.001.

[33] Yorkina, N.V., Podorozhniy, S.M., Velcheva, L.G., Honcharenko, Y.V., & Zhukov, O.V. (2020). Applying plant disturbance indicators to reveal the hemeroby of soil macrofauna species. *Biosystems Diversity*, 28(2), 181-194. doi: 10.15421/012024.
[34] Yukhnovskyi, V., Ivanenko, Y., & Lobchenko, G. (2020). Peculiarities of soil root population in spruce forests in the area of the mountain tourist network. *Proceedings of the Forestry Academy of Sciences of Ukraine*, 21, 50-59. doi: 10.15421/412025.
[35] Zhukov, O., Yorkina, N., Budakova, V., & Kunakh, O. (2021). Terrain and tree stand effect on the spatial variation of the soil penetration resistance in Urban Park. *International Journal of Environmental Studies*, 79(3), 1-17. doi: 10.1080/00207233.2021.1932368.
[36] Zuazo, V.H., & Pleguezuelo, C.R.R. (2008). Soil-erosion and runoff prevention by plant covers. A review. *Agronomy for Sustainable Development*, 28(1), 65-86. doi: 10.1051/ agro:2007062.

Вплив гірської рекреації на зміну твердості ґрунту ялинових лісів

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Анотація. Унікальність Карпатських гірських лісових екосистем, значна частина яких належить до природно-заповідних територій, приваблює щороку значні обсяги відвідувачів. Надмірна концентрація відвідувачів на популярних маршрутах призводить до рекреаційної дигресії, ущільнення ґрунтового покриву, розвитку ерозійних процесів та погіршення стану лісів. Мета роботи – встановити вплив рекреації як зовнішнього механічного діяння на ущільнення ґрунту шляхом визначення твердості ґрунту під наметом переважаючих ялинових деревостанів. Для цього вздовж двох туристичних маршрутів пенетрометром виміряно показники твердості ґрунту у межах кореневмісного шару ґрунту на чотирьох дослідних ділянках із різним віддаленням їх від полотна туристичного маршруту. Вцілому під наметом лісового деревостану ґрунтовий покрив не однорідний і отриманим показникам твердості характерна значна мінливість. Встановлено, що для туристичного маршруту «с. Зелене-Угорські скелі» на наближених до полотна стежки (до 20 м) ділянках спостерігається значне збільшення твердості ґрунту порівняно із віддаленими ділянками: на глибині 10 см вдвічі, на глибині 20 см – на 20-40 %, однак із подальшим заглибленням показники твердості вирівнюються. У той же час для популярнішого туристичного маршруту «Еколого-пізнавальна стежка «На гору Піп Іван» на прилеглій безпосередньо до полотна ділянці у верхньому 10-сантиметровому шарі твердість сягає до 19,6 кг·см$^{-2}$, а на глибині 30 см – пікових 37,8 кг·см$^{-2}$ (понад 3 МПа), що є лімітуючими значеннями для кореневаселеності ґрунту ялинових лісів. На полотні туристичних маршрутів спостерігається розвиток інтенсивних ерозійних процесів внаслідок ущільнення ґрунту із зростанням твердості ґрунту понад 60 кг·см-2 (~6 МПа). Практичне значення отриманих результатів та встановлених закономірностей полягає в доповненні існуючих методик оцінки ступеня рекреаційної дигресії у гірських умовах та можуть бути основою для проєктування заходів із врегулювання рекреаційного навантаження і відновлення порушених ділянок

Ключові слова: ущільнення ґрунту; дигресія; туристичний маршрут; пенетрометр; екосистема

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Land cover classification and urbanization monitoring using Landsat data: A case study in Changsha city, Hunan province, China

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Abstract. The United Nations predicts that by 2050, 64.1% of the developing world and 85.9% of the developed world will be urbanized. This has resulted in a rapid change in land use and land cover types in the areas surrounding cities in all countries, particularly in China, which determines the relevance of this article. The aim of the study was to evaluate the dynamics of land cover change in Changsha City, Hunan Province, China, between 2005 and 2020, using Landsat time series satellite images and the Random Forest classification algorithm. The data acquisition, pre-processing, and analysis were conducted on the Google Earth Engine (GEE) publicly available online platform.

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Land cover thematic continuous raster maps were produced using ESRI ArcGIS 10.5.1 software. The overall classification accuracy was obtained by more than 83% for every produced map and the Kappa coefficient was 0.84 and higher, which approves the reliable classification results that are close to similar recent studies in terms of obtained accuracy. The study shows that from 2005 to 2020, the area of settlement in Changsha City, China, increased significantly, with an exponential increase in urban area from 3.23% to 15.95%. The proportion of forest cover gradually decreased from 2005 to 2015 but increased from 2015 to 2020. Cropland was the second most dominant land cover type, with a peak of almost 50% in 2010. Water bodies remained stable at around 3%. The proportion of open soil and bare land cover fluctuated between 180 and 400 km2 (1.5-3%). The study suggests that the offered monitoring approach provides reliable results, and the research findings can be used for sustainable urban planning and management, as well as conservation and development initiatives. The remote sensing data and advanced GIS technologies can provide decision-makers with the accurate data to ensure sustainable development in this area

Keywords: accuracy estimation; Random Forest algorithm; satellite imagery; overall accuracy; urban expansion

Introduction

As the capital city of Hunan province and one of the most important cities in central China, Changsha has expanded at an astounding speed in recent years (Zhou & He, 2007). According to S. Su *et al.* (2011) urban expansion not only facilitates people's life, but also causes a series of environmental, transportation and climate problems; thus, affecting agriculture (Seto *et al.*, 2000), water resources and natural environment (Zhang *et al.*, 2010), even accelerating the spread of diseases (Miao & Wu, 2016) and bringing multiple challenges to urban planning and management (Batty, 2008). Y. Liu *et al*. (2021) analysed the urban expansion dynamics of the Xiaonan District in Hubei Province, China using Landsat satellite imagery and landscape metrics. The results showed that urban areas expanded rapidly during the period 1990-2020, and the expansion was accompanied by significant changes in landscape pattern and fragmentation. The study highlighted the importance of considering both the extent and pattern of urban expansion in urban planning and management.

Based on remote sensing (RS), as a non-contact technology, LULC thematic surface cover maps can be produced, including woodland, water, build-up areas and other categories. P. Corona (2010) proved that LULC distribution data can be widely applied in assessing environment and monitoring work, such as Climate change, food security, agricultural statistics (Kolotii *et al.*, 2015; Ma *et al.*, 2015) and so on. Reliable urban LULC maps can be used in more accurate urbanization process assessment and area calculation on a regional scale, which guides more effective urban planning policies. At present, various satellite systems provide objective, high spatial resolution data on a regular basis.

However, D.P. Roy *et al.* (2014) described in their work that public available medium resolution Landsat imagery, because of their continuity and long observation history, allows to regularly evaluate LULC changes in large areas. J. Friedmann (2003) concluded that under the background of the rise of Central China, the study on the expansion mechanisms of urban construction land in Changsha city can not only provide a reference for other cities of Central China to achieve sustainable development and formulate relevant policies, but also provide a case study to reveal trends of urban expansion in China. Therefore, it is crucial to study the scope and speed of urban expansion, as well as the dynamic changes of land use and land cover (LULC) in the city.

Using time series of Landsat imagery received during one calendar year or longer, various tasks of the thematic classification can be solved. Thus, the annual set of images can provide information about LULC changes of study area. Given the large number of variables (bands and band ratios) required, non-parametric methods of classification provide reliable results without the assumption that the data must have normal distribution character.

The purpose was to analyse based on multispectral satellite imagery and random forest method, the LULC distribution map of Changsha over recent 15 years period, as well as the spatial and temporal characteristics of the expansion of construction land. Based on the above mentioned, the tasks for this study were: to perform pixel based classification of Landsat time-series image composites and produce Land cover raster maps for years 2005, 2010, 2015, and 2020 within Changsha city administrative unit using Random Forest supervised classification algorithm; to determine the relationship between urban growth, agriculture and forest cover dynamics; to assess the accuracy of the obtained mapping materials and compare them with other sources and similar studies.

Literature Review

China is the country that started urbanization the earliest, develop urbanization slowly until decades ago and develop fast recently. J. Friedmann (2011) evaluates the rapid urbanization process of China as "urbanizing at breakneck speed". The number of cities has increased from 122 (in year 1950) to 674 now and the number of towns has increased from 2176 (in 1978) (Martinez *et al.*, 2017) to 16702 now.

X. Chen *et al.* (2015) described the rapid urbanization process not only accumulates national wealth, but also caused some land use, environmental and social problems in China. On social issues, over-speed urbanization has led to a phenomenon that the rural floating population only participates in the secondary labour of cities but can't really integrate into the culture, society and system of urban area, which is called "semi-urbanization", a sub-health state of the cities. On environmental issues, M. Jin *et al.* (2005), J. Zhang *et al.* (2010) found that environmental degradation such as deforestation, traffic pollution, microclimate change and so on were unavoidable in the process of urbanization. On land use issues, ever-increasing urban area has spread at an astounding rate in recent decade, however, at cropland's expense. From 1949 to 1980, almost 14667 km^2 decreased during the 30 years. H. Li *et al.* (2015) researched that during the next 15 years (from 1981 to 1995), the net loss of arable land was more than 54000 km^2.

The reasonable use of urban land can limit the over-speed of urban expansion and negative impacts. In order to make China's urbanization process in an appropriate way, people need to start with the driving force of urbanization and regulate it. L. Feng *et al.* (2017) has referred to numerous literatures and selected 4 indicators as independent variables. Through the calculation of multiple linear regression model, it is found that market force (market) is the most important driving force, followed by endogenous force (grassroots government or farmers), administrative force (government's capital policy) and extroverted force (foreign capital) (Chaolin *et al.*, 2012). Y. Yan *et al.* (2020) used Landsat images to extract land cover information and analyse spatiotemporal patterns of urban expansion in the Pearl River Delta urban agglomeration in China. This study reveals that economic development, transportation infrastructure, and population growth were the main drivers of urban expansion in the area.

The fact that the endogenous force is greater than the exogenous force indicates that China's urbanization is mainly dominated by internal factors although the world has entered the global era (Luo & Yan, 2018). Hence, it is important to know the land use and land cover change (LULC) to support the government to adopt suitable land use and distribution policies.

Land use shows how people use landscape, whether for development, conservation or mixed function (Lambin *et al.*, 2001). Land cover means that the undulating land surface (including the soil layer) covered with vegetation, snow, glaciers, or water (Lin *et al.*, 2018). Land cover has also been defined that vegetation or other features overlay on the earth surface (Song & Deng, 2017).

X. Lambin *et al*. (2001) stated that the remote sensing image classification is an important content of image analysis, which is used to estimate the area range and spatial distribution of various types of land cover, even widely applied in tropical deforestation, rangeland modifications, agricultural intensification etc. It uses computers and software to analyse the spatial information and spectral information of different objects in the image, select features, then divide the feature space into non-overlapping subspaces and finally assign each pixel in the image to the subspace (Ayanu *et al.*, 2015).

N. Puletti *et al*. (2014) found that according to the classified data of training samples are known or not, image classification algorithms can be divided into supervised classification and unsupervised classification. The Unsupervised classification has no pre-confirmed categories so that training data cannot be established. The classification is based on the difference of spectral features or other features of different images and ground objects in the feature space and the clustering statistical analysis of images can be carried out by computers.

The supervised classification of remote sensing imagery is a process which includes an extraction from training samples of each class from the known training field, and classify each pixel point in the image into each given class by selecting characteristic variables, determining discriminant function or discriminant. It refers to the process that identified pixels (pixel in the training area) recognize and analyse unrecognized pixels. In this classification, a certain number of each class on the image is selected, and based on them, the statistics or other information of each training sample area will be calculated by computers which was discussed by Y. Ayanu *et al*. (2015). Specifically, each pixel is compared with the training sample.

There are many supervised classification algorithms (classifiers). Nowadays, most commonly used non-parametric algorithms based on machine learning principles such as Random Forest, Support Vector Machine, Classification and Regression Trees, Neural Networks etc. Random forest (RF) was firstly input by L. Breiman (2001) in 2001. It is a powerful image classification technology with anti-overfitting ability, which can process segmented images and other auxiliary raster data sets. The principle and procedure are described following: The total data set consists of all training data, 2/3 training samples of it are extracted as training set. Next, the training set is put back and then the next random sampling is conducted (Simple random sampling with replacement) until the "N" time, to obtain N training sets (decision trees), which is called Bagging principle in the research conducted by V. Eisavi *et al*. (2015). We assume that these N training sets contain M feature variables totally (training feature files). Then m feature variables are extracted from each decision tree (m<M) and every result is finished. The result with the highest number of repeats (voting method) from N results becomes the final prediction result. In each sample, about 1/3 training samples which are not selected, and called as out-of-bag (OOB). OOB can be used to estimate the internal error and generate OOB error, which is used to predict the accuracy of classification (He *et al*., 2016). For the successful application of RF classifier, two parameters must be set: the number of classification trees (ntree) and the number of input variables used at each node (mtry).

From the first RS satellite Landsat 1 which was launched in 1972, in past decades, with the improvement of Remote sensing (RS) and Geographic Information System (GIS) technology, many advanced classification methods, land use and land cover change maps have been produced based on Landsat imagery analysis provided by R. Welch *et al.* (1975). M. Kutia *et al.* (2018) in their study utilised the Google earth engine (GEE) as a cloud-based platform for scientific analysis and free access for satellite imageries. It stores decades-old images and scientific datasets (at petabyte-scale). In 2008, with the free availability of the Landsat series, Google archived all datasets and linked them to the cloud computing engine, for acquisition of open-source data according to O. Firpi (2016). The GEE computing engine provides both JavaScript and Python application programming interfaces (apis) that is allowed to easily develop algorithms that work in parallel on a Google data computer facility.

Materials and Methods

Study area. Changsha is the capital and most populous city of Hunan province (27°51′-28°41′N, 111°53′-114°15′E) (Fig. 1) in the south-central part of the People's Republic of China, covering approximately 11 819 km^2 (about 230 kilometers long from east to west and 88 kilometers wide from south to north). Also, it is an important central city in the middle reaches of the Yangtze River. It is about 118-127 days in summer, 117-122 days in winter, and 61-64 days in spring and 59-69 days in autumn (Zhou & He, 2007). Changsha has a subtropical monsoon climate. The annual average high temperature is 22.0°C and the low is 13.3°C. The annual rainfall is around 1615.4 mm. The average annual air pressure is 101 thousand PPA. The average annual sunshine period is 1640-1700 hours and the relative humidity is 81% (Yao *et al.*, 2018).

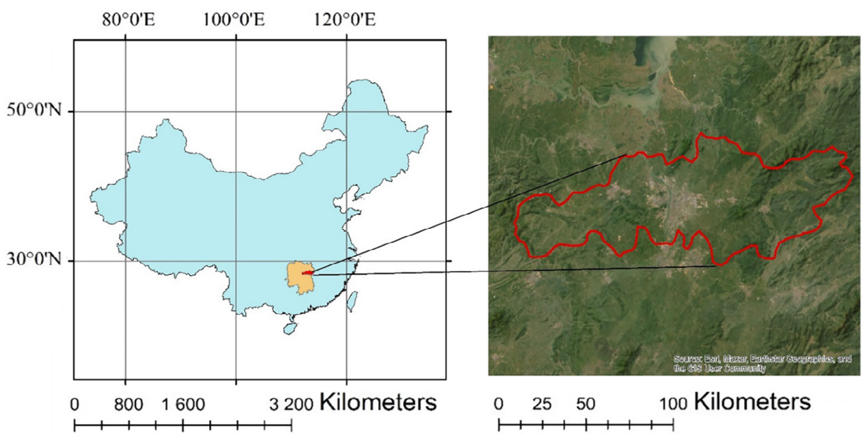

Figure 1. The location of Changsha City in Hunan Province, P.R. of China

Source: Esri, Maxar, Earthstar Geographics, and the GIS User Community

It is surrounded by mountains which are relatively high at both the northeast and northwest; while the central part is gentle, therefore looking likes a saddleback. Xiangjiang River runs through the central part from the south to the north, and the southern part is hilly and undulating, in contrast, the northern part is flat and open (Tse-Tung, 2017). Red soil and paddy soil is main soil in Changsha, accounting for 70% and 25% of the total soil area respectively (Tian *et al.*, 2017). Xiangjiang River is the main river of Changsha and there are 15 tributaries flowing into it, including Liuyang River, Laodao River, Jinjiang River and so on. There are abundant water resources. Water does not freeze in winter and contains little sand (Tian *et al.*, 2018).

Training data creation and remote sensing imagery acquisition. The boundary of Changsha is acquired from open source GADM data. (n.d.) which contains World countries boundary as a vector ESRI shp files. Given the large area of Changsha city a big size of training data is required to achieve a satisfied classification accuracy. Firstly, the systematic sampling design was carried out within the official Changsha city boundary which includes most common land cover types, and the distance between each sampling point is set as 10x10 km. For each year of observation, authors have created 106 polygons (as a buffer around each sampling point) with 5 cover classes: cropland, forest, open soil or bare land, settlement areas, and water bodies. Using the designed network of sampling points the training polygons of different land cover types were drawn in Google Earth Pro software using time slider tool in order to select the background imagery for the indicated time (year). Using zooming tool, authors carefully analysed land cover types and drawn training polygons. Given that, it was prepared the dataset of training polygons for each year of study that cover a considerably big number of pixels as follows: 2005 – 15631 pixels; 2010 – 16345 pixels, 2015 – 14765 pixels; and 2020 – 18851 pixels respectively. The minimum number of pixels (856) were observed for the smallest land cover class – open soil or bare land, the rest of classes were represented with the more than 1000 reference pixels. The generated reference polygons were converted into vector layer then imported into Google Earth Engine platform and ArcGIS software for further analysis.

There are various classification standards of LULC types, such as the criteria provided by United Nations, Natural Resources Defense Council (NRDC), U.S. Geological Survey (USGS) and so on. For our study the main purpose was to locate the land cover changes especially settlement areas, woodlands and croplands, the five-fold LULC class system was selected with the following classes:

- *Cropland.* Cropland includes most flat areas and some steep slopes where a variety of food crops and some low height grass vegetation are grown, either feed on rainwater or irrigation. In Changsha, irrigation is a common practice, because there are significant seasonal differences in rainfall, mainly in the spring.
- *Forest.* Forest is the area dominated by woody plants, also including other plants, animals, microorganisms. It has abundant species, complex structure and various functions. The shrublands has been also included into this land cover category.
- *Open soil and bare land* (also named as *"Other land"* in this manuscript). Other land mainly includes bare land (it is not covered by any crop, grass or any other shrub or tree species, mainly including exposed sand, salt flats and exposed rock or cleared territories before construction process. (WBISPP, 2002).
- *Settlements.* It is a large residential area formed by non-agricultural industry and non-agricultural population agglomeration, usually have a dense population. This category

includes both urban land and rural settlements (Esetlili & Sunar, 2017).

❖ *Water bodies*. It is the general term for the liquid that forms the surface of the earth in nature. It includes rivers, oceans, glaciers, lakes, marshes, and other surface water bodies. The water cover type in Changsha is represented mainly in the form of rivers, irrigation canals, and lakes.

Based on this classification scheme, the training polygons have been created. It should be noticeable the number of polygons in a class must be corresponding to the real area of that class, which means that the larger the area, the more polygons are taken in the class, and vice versa. The size of each polygon was chosen with the assumption that each polygon must cover at least 10 pixels of Landsat image (30x30 m). Polygons should be a convex shape, not a concave one. Also, polygons should be drawn in the middle of the class, as far as possible away from edge to avoid possible confusions during training the classifier procedure.

Compilation of the remote sensing data was performed using the Google Earth Engine API (GEE). GEE uses state-of-the-art cloud-computing and storage capabilities that have been archived in a large catalogue of earth observation data. It is highly efficient to work on petabytes of satellite imagery rapidly using parallel cloud computing on the Google servers. GEE platform works on JavaScript programming language. Most importantly, using GEE it was possible to develop our own script which allowed us to apply all the necessary filters and prepare yearly Landsat image mosaics with the median values of reflectance. Another important advantage of the use of GEE was the possibility to select already corrected Landsat images. Using specifically developed algorithm all Landsat images went through radiometric and top of atmosphere (TOA) corrections (Midekisa *et al.*, 2017).

In this study Landsat 7 was used for Changsha city land cover classification in 2005 and 2010; Landsat 8 was used in 2015 and 2020 respectively. Landsat satellite data, that were used in this research, are free available satellite imageries with both moderate spatial and spectral resolution without clouds. The Landsat-8 satellite payload consists of two science instruments –the Operational Land Imager (OLI) and the Thermal Infrared Sensor (TIRS). These two sensors provide seasonal coverage of the global landmass at a spatial resolution of 30 meters (visible, NIR, SWIR); 100 meters (thermal); and 15 meters (panchromatic). TIRS images consist of nine spectral bands with a spatial resolution of 30 meters for Bands 1 to 7 and 9. New band 1 (ultra-blue) is useful for coastal and aerosol studies. New band 9 is useful for cirrus cloud detection (Mateo-García *et al.*, 2018). The resolution for Band 8 (panchromatic) is 15 meters. Thermal bands 10 and 11 are useful in providing more accurate surface temperatures and are collected at 100 meters (Irene *et al.*, 2017). The images in this study were taken in 2005 (Landsat 7), 2010 (Landsat 7), 2015 (Landsat 8), and 2020 (Landsat 8) respectively.

To get more cloud-free images, the starting and ending times are set to be two months before and two months after the target year. After that, another filter was applied based on cloud score (percentage of cloud cover on the image). In this case images with cloud score less than 5% were selected and ranked by the principle: lowest cloud cover on top and biggest – on the bottom. Finally, to get yearly image composite authors used median value of every pixel of study area out of the selected images set. The only 30 m resolution spectral bands and some simple band ratios of Landsat images have been selected for the future classification. For the Landsat 8 authors used near infrared (NIR) and thermal bands: Band 2 (0.45-0.52 μm), Band 3 (0.525-0.60 μm), Band 4 (0,64-0,67 μm), Band 5

(0,85-0,88 μm), Band 6 (1,57-1,65 μm), Band 7 (2,11-2,29 μm), Band 10 (10,60-11,19 μm), Band 11 (11,50-12,51 μm) as well as band ratio recommended by V. Myroniuk *et al.* (2020) as follows: Band 4 / Band 5, Band 4 / Band 7, Band 5 / Band 7. Finally, the NDVI index.

As a result, the whole year image composite has been created with 11 bands ready for the classification, based on Landsat Image time series. The same approach was applied for each target year.

Random Forest classifier settings. The programming script in GEE environment has been developed by authors and run Random Forest algorithm for the classification of study area using training polygons and Landsat yearly composites for each target year 2005, 2010, 2015 and 2020 accordingly. Basic settings of RF classifier were as follows: number of decision trees: 500; OBB mode used; fraction of data for each iteration: 67%; portion of training data for error estimation: 33%; number of variables per split in every node: 11.

Using the training datasets, authors performed firstly the training accuracy estimation of the classifier for each year. It has been obtained more than 97% overall training accuracy of the RF classification based on the reference pixels. Having satisfied results of training overall accuracy it was concluded that the RF classifier is ready for the classification of the entire study area. After the conducting the classification procedure in GEE environment, 4 raster classified raster images of Changsha city for the target observation years have been produced and then exported these rasters into ArcGIS software for further analysis.

The next step was accuracy assessment of the obtained raster land cover maps of Changsha city at the indicated years. To do this, it is needed to evaluate the differences between classified data and ground truth data (accurate data), which helps users to know if the data is reliable or not (Stehman & Czaplewski, 1998). In this study, authors analysed the LULC changes of Changsha which is quite big area. Hence, gathering of field references data using GPS or aerial photos is time consuming and expensive, therefore choose multiple resolution imagery and Google Earth software were used. Simple random sampling method was utilized for preparing the network of validation points. The total number of points is dependent on the number of classes and sampling strategy. According to the standard principle that the minimum required number has to be no less than 50 points in each land cover class. In our case, having 5 classes, at least 250 validation points should be created. As the area of interest is constant, the number of random points is proportional to the area of the corresponding class. Due to the small coverage of some categories such as bare land and water, the points covered by them are likely to be less than 50. Hence, there were more than 500 random points created for each year. A standard accuracy assessment procedure was applied by authors that requires construction of error matrix, calculation of User's, Producer's, Overall accuracy percentage, and Kappa statistics (Rwanga & Ndambuki, 2017).

Results

Changsha city land cover classified raster maps. Using ArcGIS 10.5 software and classified Landsat image composites previously prepared in GEE by the described above approach, four continuous thematic land cover raster maps have been produced of Changsha for year 2005, 2010, 2015 and 2020. The mapping results are shown on the Figure 2.

Form the Figure 2, the Changsha urbanized area was divided into two parts along the Xiangjiang River. The left riverbank mostly represented as farmlands and the right – mostly forests. The highest density of buildings is mainly concentrated in the middle of study area along the Xiangjiang River. From 2005 to 2010, the urban area expanded further along Xiangjiang riverbanks where urban settlements of Changsha originated. However, the area of forests was taken by urban area and cropland as the total area of Changsha did not change. From 2010 to 2015, the newly increased urban spots were scattered across the study area which is usually described as 'patches' in landscape field. The forest area increased slightly during that period. From 2015 to 2020, some patches of settlements became interconnected. At the same time, the size of patches doubled at cropland area's expense. The overall layout of Changsha showed that based on the settlement center around Xiangjiang River, small settlements spread out within the study boundary.

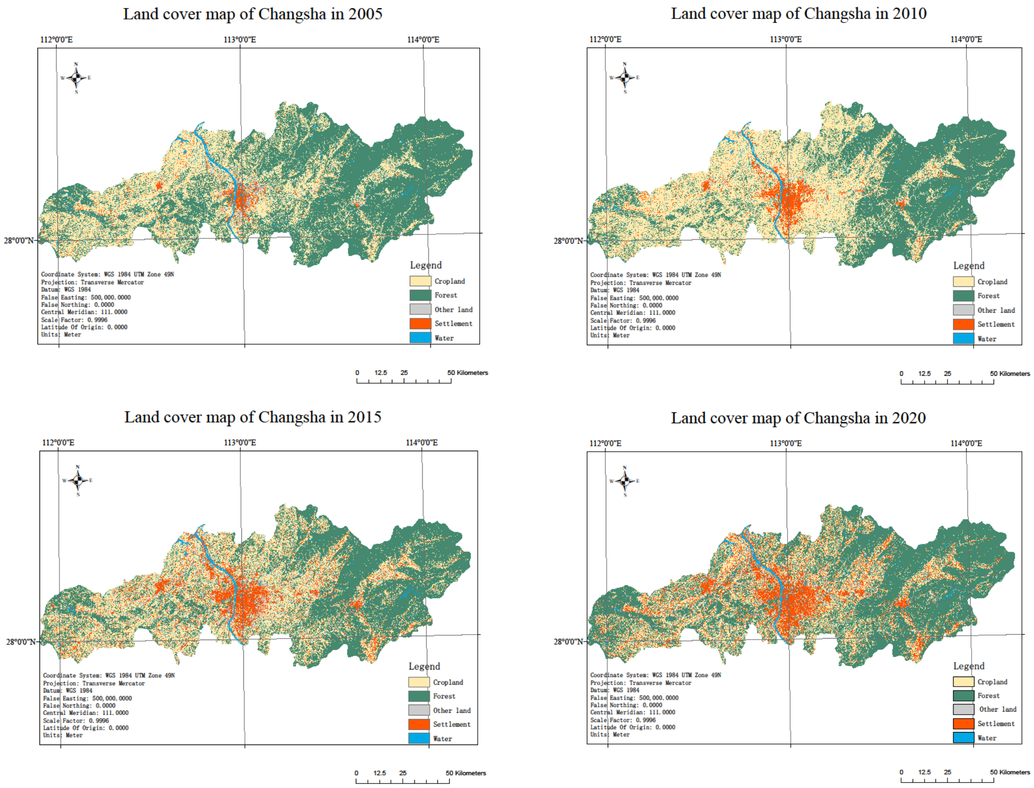

Figure 2. The classified land cover raster maps of Changsha city in 2005, 2010, 2015, and 2020
Source: developed by the authors

With the aim to check the accuracy of the obtained results, authors used common approach which based on the preparation of the sets of reference points, creation error matrix and calculate User's, Producer's and Overall accuracies and finally, Kappa statistics.

Accuracy assessment of the classification results. The of the accuracy assessment have been performed according to the described above procedure. The error matrix was created based on the sets of specifically created validation points for each year of observation

(500 point for each year). The overall accuracy, as well as User's and Producer's accuracies and Kappa statistics are provided in the Table 1.

The overall accuracy in 2020, 2015, 2010 and 2005 are 85.13%, 86.09%, 87.15% and 83.80% respectively. The Kappa coefficient is 0.84 and higher, which approves high level of the classification results. The producer's accuracy of forestland cover type and water bodies demonstrated the highest levels of accuracy (90% or higher) compared with the other classes. It can point out that User's accuracy commonly has higher values than Producer's. The settlements cover class identification has also shown satisfied levels of both Producer's and user's accuracies (close to 80% and higher.

Table 1. The accuracy calculation results for the produced land cover maps of Changsha city

Year of observation		2020	2015	2010	2005
Overall Acc, %		85.13	86.09	87.15	83.80
Kappa coefficient		0.84	0.85	0.86	0.84
Producer's Accuracy, %	Cropland	88.24	90.74	92.62	84.92
	Forest	92.91	95.05	89.80	94.69
	Other land	88.46	77.97	76.56	76.10
	Settlements	77.92	84.85	80.28	76.00
	Water	97.50	83.87	94.83	88.14
User's Accuracy, %	Cropland	85.29	75.38	83.09	82.31
	Forest	89.37	90.57	92.31	86.29
	Other land	88.46	88.00	81.67	75.00
	Settlements	80.00	78.87	86.36	81.43
	Water	91.76	98.11	96.49	92.86

Source: developed by the authors

Changsha city land cover change dynamics during the period 2005 to 2020. According to the obtained land cover raster maps of Changsha city the proportion of each land cover type in different years is calculated in ArcGIS software and expressed in the form of percentage in year 2005, 2010, 2015 and 2020 (Fig. 3).

During the period 2005-2020, the percentage of forest is the highest (almost half a pie in each year) except for that in 2010. The proportion of cropland is closed to 36% in both year of 2005 and 2015. In 2010, it reaches the top with almost 50% of total area. The proportion of water bodies have not been changes significantly and it always shows a small percent about 3% only. The proportion of other (open soil and bare land) land cover class is the lowest among the five types during the whole study period. It takes up around 5.5% in 2010, which is the highest one. The proportion of urban area has been increased exponentially from 3.23% in 2005 to 15.95% in 2020.

The dynamics of urban (settlements cover type) area for the study period in absolute units (km^2) are shown on the Figure 4.

In general, the area of settlement has increased during the 15-year period from 380.4363 km^2 to 1880.1756 km^2 (1499.7393 km^2 totally increase). The area of forests decreases gradually from 2005 to 2015, however there is an increasing trend during 2015-2020, from 5281 to 6089 km^2 respectively. Figure 4 shows that from year 2005 to 2010, there is an increase of the area from 4239 to 5527 km^2, and then during the following ten years, it decreases to 3230 km^2 only. As for the open soil and other bare land cover, it fluctuates between 180 and

400 km². The highest area observed in 2015 (398 km²) which can be explained as a high intensity of contraction process at that period. Analysis of the water cover change shows that the change is generally small. The minimum value of 267 km² was obtained in 2010 and a peak of 392 km² in 2020. This can be explained as the development of irrigation canals and water reservoirs within the city when doing landscape design of the new residential areas.

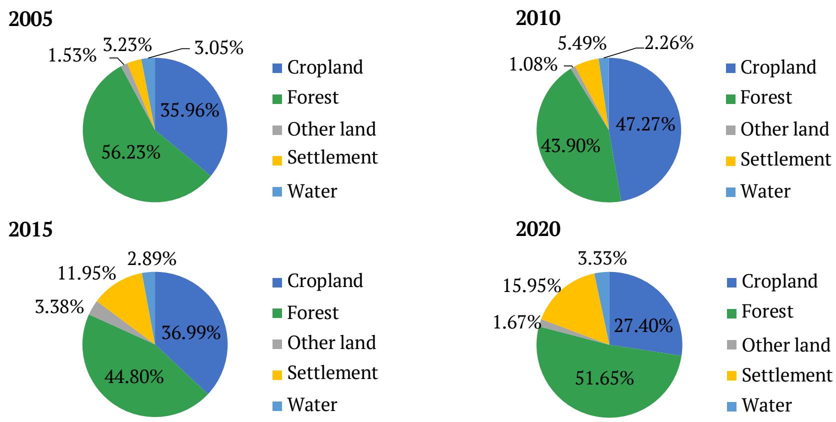

Figure 3. The percentage of different land cover types of Changsha city for the four observation years (2005, 2010, 2015, and 2020)

Source: developed by the authors

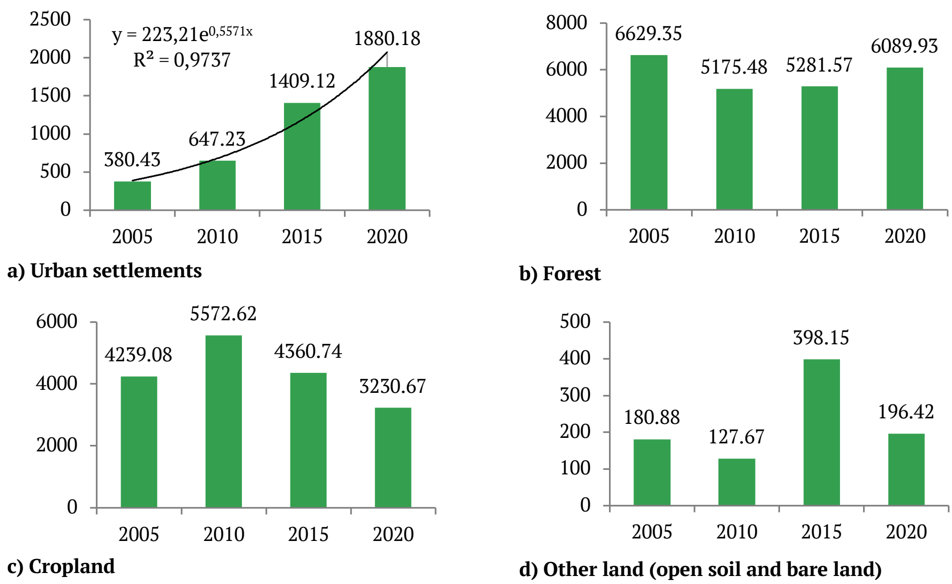

Figure 4. The dynamic change of the main land cover types (in km²) of Changsha city in 2005-2020

Source: developed by the authors

The analysis of factors that may cause an impact on Changsha urban areas expansion. *Natural environment* is the basic restriction condition of urban space expansion. Changsha city is located in the transition zone from hills to plains, so the landform of this range is diversified. Specifically, the west side of the city is low mountainous area, the northeast side is granite low hilly area, the north part has dense and developed river network, the south is low hilly area and only the middle part is flat terrain. Considering of the cost of urban constructions, the input of infrastructure in the plain area is significantly lower than that in the hill area and it is easy to arrange industrial projects and residential areas, which determines that the urban construction of Changsha takes the Xiangjiang River as the central axis and presents a north-south urban development pattern. Due to the restriction of mountain barriers and water system division, the city cannot spread continuously like cities with flat terrain.

Economic development, transportation development and population growth. The growth of urban population and economy is the basic power of urban land expansion. On the one hand, the growth of urban economy itself needs more land as support. On the other hand, the rural-shift to-urban population increases urban load-bearing pressure. In addition, the neglect of the old city reconstruction has made the problem of urban land extension faster. Some research studies show that the distribution of traffic network and urban settlements has a linear relationship (Poumanyvong *et al.*, 2012). In recent years, Changsha High-speed Railway station (2009), Changsha Metro (2014), Changsha-Zhuzhou-Xiangtan Intercity Railway (2017) were constructed and operated on a regular basis, which provides the urban industries and companies nearby with a wide accessibility to various destinations (Kotavaara, Antikainen and Rusanen, 2011), therefore population increased as much employment was provided.

Planning policies of urban areas development and design. According to urban planning policies of Changsha government, 2500 km^2 area adjacent to the core development area of Changsha is planned as ecological protection zone and urban constructions are forbidden there that helps to protect the forested areas efficiently. Urban underground spaces should be developed to reduce the occupation of new urban land, therefore protecting farmland areas, and other local regulations.

This study with the proposed LULC mapping approach might be useful for solving various important tasks related to the continuous monitoring of the land cover changes. This may become a basis for the ecosystem service valuation procedures and might help the Changsha government and decision makers to support a sustainable city land use planning in order to receive economic benefits as well as valuable ecosystem services. The conducted research helps to control the increase rate of settlement land category strictly and make great focus on conservation and increase the areas of woodland and water body which could provide a greater level of ecosystem services.

Discussion

Similar studies that were based on the use of RF classifier and Landsat time-series imagery demonstrated close results of accuracy assessment comparing to ours. For example, the land cover map of Changsha City using Landsat 8 datasets and pixel-based method classification approach published by Z. Deng *et al.* (2019) demonstrated 88.62% of overall accuracy and 0.83 Kappa coefficient. The overall classification accuracy using Landsat 8 OLI data with feature selection reached 82% in a case study of land cover mapping in Yunnan Province, China (Pan *et al.*, 2022). Another land cover map produced for the eastern edge of the Tibetan Plateau in the north of Sichuan Province, China

(Zhu, 2013) showed overall accuracy of the 82% with a Kappa coefficient of agreement of 0.73. Therefore, it can be stated that the prepared training dataset size in combination with the suggested Landsat time series image composite as well as proper RF classifier settings demonstrated reliable classification results.

The effectiveness of RF algorithm and Landsat time-series data to analyse land use and land cover change have been investigated by S. Amini *et al*. (2022). The impact of different image compositions and auxiliary data, such as digital elevation model (DEM) and land surface temperature (LST), on final classification accuracy was also explored. The proposed algorithm achieved high accuracy levels, with an overall accuracy of 94.438%, Kappa of 0.93. The algorithm's success in obtaining high accuracies indicates its potential for efficient extraction of spatiotemporal information for LULC classification. The three LULC maps have been created for 2010, 2015, and 2020 in Rahuri watershed area, India using the google earth engine and RF classifier (Pande, 2022). Similar to our study, the entire three years of land use and land cover produced high accuracy (OA ranges from 85.53% to 94.34%). Agriculture and built-up land were divided with the greatest precision, followed by forest and other land. The author approves that GEE is a successful platform for accessing and processing satellite data through the use of various classification algorithms in combination with geographic object-oriented or pixel-based analysis techniques. The study conducted by G. Ge *et al.* (2020) compares the performances of four most popular machine learning algorithms in classifying land use and cover change in the Dengkou Oasis region of China using Landsat-8 OLI image data. The study finds that artificial neural networks has the highest overall accuracy (97.16%), followed by RF (96.92%), SVM (96.20%), and KNN (93.98%). RF is recommended as a good first choice method for land-cover classification in this study area.

J. Cui *et al.* (2022) investigated land use/land cover changes and their driving factors in the Yellow River Basin of Shandong Province, China, using Google Earth Engine from 2000 to 2020. The results showed that the main changes in land use/land cover were the increase in construction land and decrease in cultivated land, woodland, and grassland. The overall accuracy exceeded 86% indicating that the classification results were reasonable and reliable. The changes were primarily driven by population growth, economic development, and urbanization. The Random Forest classifier was found to be an effective method for mapping land use/land cover in the study area.

S. Feng *et al*. (2022) utilized the Google Earth Engine (GEE) platform to conduct land use classification in a large area with a complex workflow, achieving fast and accurate results. The pixel-based Random Forest (RF) classification method was used for land use classification, which yielded overall accuracy above 87% and kappa coefficient 0.88 that met the requirements. However, due to the absence of object-oriented thinking, the method produced some salt and pepper noise that is similar to our study. Therefore, future research should focus on the integration of image segmentation and feature matching to improve the land use classification method in the study area. The RF algorithm demonstrated potential to work with various datasets, high-dimensional data, and interaction between features during training, while having a fast training pace and low computing cost. RF showed a minimum accuracy of 79.54% in a study conducted by B. Feizizadeh *et al.* (2023). It confirms decent performance with minimal tendency to overfit and has been applied to various applications such as landslide susceptibility mapping, sustainability assessment, and landform mapping.

The results of our study indicates that the use of LULC maps and change detection based on them are recognized as valuable for various applications, including land use planning and allocation, environmental impact analysis, and assessment of sustainable development. The outcome of this research can be essential for decision makers and authorities in local governmental departments and stakeholders to observe the environmental issues of the Changsha city in the next decades.

Conclusions

In this paper, a comprehensive approach of land use/cover mapping was enriched. The described method demonstrates the potential possibilities of the use Landsat time-series image composites and RF classifier for the LULC mapping and monitoring changes for the Changsha city study area. GEE platform provides a wide range of abilities to search, filter and process of a huge amounts and types of spatial-temporal remote sensing data. The produced continuous land cover raster maps of Changsha city enable us to do the monitoring of land cover change dynamic for the period 2005-2020. From 2005 to 2020, the proportion of urban area has been gradually increased from 3.23% to 15.95% and the area has increased by 1500 km^2. However, the area of cropland has declined by 1008 km^2, however, forestland class shows a growth trend at the latest 5 years observation period. The accuracy assessment result allows us to make a conclusion that chosen approach can be successfully used for solving tasks related to classification and monitoring of city land cover changes. Further research could focus on the integration of additional data sources, such as high-resolution imagery and LiDAR data, and classification algorithms for better identification of different land cover types and more accurate mapping of urban areas.

Conflict of Interest

The authors declare no conflict of interest.

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References

[1] Amini, S., Saber, M., Rabiei-Dastjerdi, H., & Homayouni, S. (2022). Urban land use and land cover change analysis using random forest classification of Landsat time series. *Remote Sensing*, 14(11), article number 2654. doi: 10.3390/rs14112654.
[2] Ayanu, Y., Conrad, C., Jentsch, A., & Koellner, T. (2015). Correction: Unveiling undercover cropland inside forests using landscape variables: A supplement to remote sensing image classification. *PLoS ONE,* 10(8), article number e0137150. doi: 10.1371/journal.pone.0137150.
[3] Banerjee, B., & Buddhiraju, K. (2015). A novel semi-supervised land cover classification technique of remotely sensed images. *Journal of the Indian Society of Remote Sensing. New Delhi: Springer India,* 43(4), 719-728. doi: 10.1007/s12524-014-0370-z.
[4] Batty, M. (2008). The size, scale, and shape of cities. *Science. American Association for the Advancement of Science*, 319(5864), 769-771. doi: 10.1126/science.1151419.
[5] Breiman, L. (2001). Random forests. *Machine Learning,* 45, 5-32. doi: 10.1023/A:1010933404324.
[6] Chaolin, G., Liya, W., & Cook, I. (2012). Progress in research on Chinese urbanization. *Frontiers of Architectural Research*, 1(2), 101-149. doi: 10.1016/j.foar.2012.02.013.

[7] Chen, X., Yu, B., Zhou, D., Zhou, W., Gong, J., Li, S., & Stanton, B. (2015) A comparison of the number of men who have sex with men among rural-to-urban migrants with non-migrant rural and urban residents in Wuhan, China: A GIS/GPS-assisted random sample survey study. *PLoS ONE*, 10(8), article number e0134712. doi: 10.1371/journal.pone.0134712.

[8] Corona, P. (2010). Integration of forest mapping and inventory to support forest management. *IForest – Biogeosciences and Forestry*, 3(3), 59-64. doi: 10.3832/IFOR0531-003.

[9] Cui, J., Zhu, M., Liang, Y., Qin, G., Li, J., & Liu, Y. (2022). Land use/land cover change and their driving factors in the Yellow River Basin of Shandong Province based on Google Earth Engine from 2000 to 2020. *ISPRS International Journal of Geo-Information*, 11(3), article number 163. doi: 10.3390/ijgi11030163.

[10] Deng, Z., Zhu, X., He, Q., & Tang, L. (2019). Land use/land cover classification using time series Landsat 8 images in a heavily urbanized area, *Advances in Space Research*, 63(7), 2144-2154. doi 10.1016/j.asr.2018.12.005.

[11] Eisavi, V., Homayouni, S., Yazdi, A.M., & Alimohammadi, A. (2015). Land cover mapping based on random forest classification of multitemporal spectral and thermal images. *Environmental Monitoring and Assessment*, 187, 1-14. doi: 10.1007/s10661-015-4489-3.

[12] Esetlili, M., & Sunar, F. (2017). Evaluation of image fusion methods using PALSAR, RADARSAT-1 and SPOT images for land use/ land cover classification. *Journal of the Indian Society of Remote Sensing. Dordrecht: Springer Science & Business Media*, 45(4), 591-601. doi: 10.1007/s12524-016-0625-y.

[13] Feizizadeh, B., Omarzadeh, D., Garajeh, M. K., Lakes, T., & Blaschke, T. (2023). Machine learning data-driven approaches for land use/cover mapping and trend analysis using Google Earth Engine. *Journal of Environmental Planning and Management*, 66(3), 665-697. doi: 10.1080/09640568.2021.2001317.

[14] Feng, L., Chen, B., Hayat, T., Alsaedi, A., & Ahmad, B. (2017). The driving force of water footprint under the rapid urbanization process: a structural decomposition analysis for Zhangye city in China. *Journal of Cleaner Production. Elsevier Ltd*, 163(S), S322-S328. doi: 10.1016/j.jclepro.2015.09.047.

[15] Feng, S., Li, W., Xu, J., Liang, T., Ma, X., Wang, W., & Yu, H. (2022). Land use/land cover mapping based on GEE for the monitoring of changes in ecosystem types in the upper Yellow River Basin over the Tibetan Plateau. *Remote Sensing*, 14(21), article number 5361. doi: 10.3390/rs14215361.

[16] Firpi, O.A.A. (2016). Satellite data for all? Review of Google Earth Engine for archaeological remote sensing. *Internet Archaeology. University of York,* 42. doi: 10.11141/ia.42.10.

[17] Friedmann, J. (2003). China's Urbanization. *International Journal of Urban and Regional Research*, 27(3), 745-758. doi: 10.1111/1468-2427.00480.

[18] Friedmann, J. (2011). Becoming urban: Periurban dynamics in Vietnam and China – introduction. *Pacific Affairs*, 84(3), 425-434. doi: 10.5509/2011843425.

[19] GADM data. (n.d.). Retrieved from https://gadm.org/data.html.

[20] Ge, G., Shi, Z., Zhu, Y., Yang, X., & Hao, Y. (2020). Land use/cover classification in an arid desert-oasis mosaic landscape of China using remote sensed imagery: Performance assessment of four machine learning algorithms. *Global Ecology and Conservation*, 22, article number e00971. doi: 10.1016/j.gecco.2020.e00971.

[21] He, C., Zhanga, D., Huanga, Q., & Zhao, Y. (2016). Assessing the potential impacts of urban expansion on regional carbon storage by linking the LUSD-urban and InVEST models. *Environmental Modelling and Software*, 75, 44-58. doi: 10.1016/j.envsoft.2015.09.015.

[22] Martinez, H.M., & Cartier, C. (2017). City as province in China: The territorial urbanization of Chongqing. *Eurasian Geography and Economics. Routledge*, 58(2), 201-230. doi: 10.1080/15387216.2017.1312474.

[23] Jin, M., Dickinson, R., & Zhang, D. (2005). The footprint of urban areas on global climate as characterized by MODIS. *Journal of Climate*, 18(10), 1551-1565. doi: 10.1175/JCLI3334.1.

[24] Kolotii, A., Kussul, N., Shelestov, A., Skakun, S., Yailymov, B., Basarab, R., Lavreniuk, M., Oliinyk, T., & Ostapenko, V. (2015). Comparison of biophysical and satellite predictors for wheat yield forecasting in Ukraine. *ISPRS*, XL-7/W3, 39-44. doi: 10.5194/isprsarchives-XL-7-W3-39-2015.

[25] Kutia, M., Myroniuk, V., & Sarkissian, A. (2018). Evaluation of Sentinel-2 composited mosaics and random forest method for tree species distribution mapping in suburban areas of Kyiv City, Ukraine. In *Proceedings of the International Workshop on Environmental Management, Science and Engineering – IWEMSE* (pp. 597-604). Xiamen, China. doi: 10.5220/0007563505970604.

[26] Lambin, E.F., Turner, B.L., Geist, H.J., Agbola, S.B., Angelsen, A., Bruce, J.W., Coomes, O.T., Dirzo, R., Fischer, G., Folke, C., George, P.S., Homewood, K., Imbernon, J., Leemans, R., Li, X., Moran, E.F., Mortimore, M., Ramakrishnan, P.S., Richards, J.F., Skånes, H., Steffen, W., Stone, G.D., Svedin, U., Veldkamp, T.A., Vogel, C., & Xu, J. (2001). The causes of land-use and land-cover change: Moving beyond the myths. *Global Environmental Change,* 11(4), 261-269. doi: 10.1016/S0959-3780(01)00007-3.

[27] Li, H., Huang, X., Kwan, M.-P., Bao, H.X.H., & Jefferson, S. (2015). Changes in farmers' welfare from land requisition in the process of rapid urbanization. *Land Use Policy*, 42, 635-641. doi: 10.1016/J.LANDUSEPOL.2014.09.014.

[28] Lin, B.B., Egerer, M.H., Liere, H., Jha, Sh., Bichier, P., & Philpott, S.M. (2018). Local- and landscape-scale land cover affects microclimate and water use in urban gardens. *Science of the Total Environment*, 610-611, 570-575. doi: 10.1016/j.scitotenv.2017.08.091.

[29] Liu, Y., Zuo, R., & Dong, Y. (2021). Analysis of temporal and spatial characteristics of urban expansion in Xiaonan district from 1990 to 2020 using time series Landsat imagery. *Remote Sensing*, 13(21), article number 4299. doi: 10.3390/rs13214299.

[30] Luo, S., & Yan, W. (2018). Evolution and driving force analysis of ecosystem service values in Guangxi Beibu gulf coastal areas, China. *Acta Ecologica Sinica,* 9, article number 3248. doi: 10.5846/stxb201704050578.

[31] Ma, Y., Wu, H., Wang, L., Huang, B., Ranjan, R., Zomaya, A.Y., & Jie, W. (2015). Remote sensing big data computing: Challenges and opportunities. *Future Generation Computer Systems*, 51, 47-60. doi: 10.1016/j.future.2014.10.029.

[32] Mateo-García, G., Gómez-Chova, L., Amorós-López, J., Muñoz-Marí, J., & Camps-Valls, G. (2018). Multitemporal cloud masking in the Google Earth Engine. *Remote Sensing*, 10(7), article number 1079. doi: 10.3390/rs10071079.

[33] Miao, J., & Wu, X. (2016). Urbanization, socioeconomic status and health disparity in China. *Health & Place*, 42, 87-95. doi: 10.1016/j.healthplace.2016.09.008.

[34] Midekisa, A., Holl, F., Savory, D.J., Andrade-Pacheco, R., Gething, P.W., Bennett, A., Andrade-Pacheco, R., Gething, P., Bennett, A., & Sturrock, H. (2017). Mapping land cover change over continental Africa using Landsat and Google Earth Engine cloud computing. *PLoS ONE*, 12(9), article number e0184926. doi: 10.1371/journal.pone.0184926.

[35] Myroniuk, V., Kutia, M., Sarkissian, A.J., Bilous, A., & Liu, S. (2020). Regional-scale forest mapping over fragmented landscapes using global forest products and Landsat time series classification. *Remote Sensing*. 12(1), article number 187. doi: 10.3390/rs12010187.

[36] Pan, J., Wang, C., Wang, J., Gao, F., Liu, Q., Zhang, J., & Deng, Y. (2022). Land cover classification using ICESat-2 photon counting data and Landsat 8 OLI Data: A case study in Yunnan Province, China. *IEEE Geoscience and Remote Sensing Letters*, 19, article number 2507405. doi: 10.1109/LGRS.2022.3209725.

[37] Pande, C.B. (2022). Land use/land cover and change detection mapping in Rahuri watershed area (MS), India using the google earth engine and machine learning approach. *Geocarto International,* 37(26), 13860-13880. doi: 10.1080/10106049.2022.2086622.

[38] Poumanyvong, P., Kaneko, S., & Dhakal, S. (2012). Impacts of urbanization on national transport and road energy use: Evidence from low, middle and high income countries. *Energy Policy,* 46, 268-277. doi: 10.1016/J.ENPOL.2012.03.059.

[39] Puletti, N., Perria, R., & Storchi, P. (2014). Unsupervised classification of very high remotely sensed images for grapevine rows detection. *European Journal of Remote Sensing*, 47, 45-54. doi: 10.5721/EuJRS20144704.

[40] Roy, D.P., Wulder, M.A., Loveland, T.R., Woodcock, C.E., Allen, R.G., Anderson, M.C., Helder, D., Irons, J.R., Johnson, D.M., Kennedy R., Scambos, T.A., Schaaf, C.B., Schott, J.R., Sheng, Y., Vermote, E.F., Belward, A.S., Bindschadler, R., Cohen, W.B., Gao, F., Hipple, J.D., Hostert, P., Huntington, J., Justice, C.O., Kilic, A., Kovalskyy, V., Lee, Z.P., Lymburner, L., Masek, J.G., McCorkel, J., Shuai, Y., Trezza, R., Vogelmann, J., Wynne, R.H., & Zhu, Z. (2014). Landsat-8: Science and product vision for terrestrial global change research. *Remote Sensing of Environment*, 145, 154-172. doi: 10.1016/J.RSE.2014.02.001.

[41] Rwanga, S., & Ndambuki, J. (2017). Accuracy assessment of land use/land cover classification using remote sensing and GIS. *International Journal of Geosciences,* 8, 611-622. doi: 10.4236/ijg.2017.84033.

[42] Seto, K.C., Kaufmann, R.K., & Woodcock, C.E. (2000). Landsat reveals China's farmland reserves, but they're vanishing fast. *Nature,* 406(6792), article number 121. doi: 10.1038/35018267.

[43] Song, W., & Deng, X. (2017). Land-use/land-cover change and ecosystem service provision in China. *Science of The Total Environment*, 576, 705-719. doi: 10.1016/J.SCITOTENV.2016.07.078.

[44] Stehman, S.V., & Czaplewski, R.L. (1998). Design and analysis for thematic map accuracy assessment: Fundamental principles. *Remote Sensing of Environment,* 64, 331-344. doi: 10.1016/S0034-4257(98)00010-8.

[45] Su, S., Jiang, Z., Zhang, Q., & Zhang, Y. (2011). Transformation of agricultural landscapes under rapid urbanization: A threat to sustainability in Hang-Jia-Hu region, China. *Applied Geography*, 31(2), 439-449. doi: 10.1016/j.apgeog.2010.10.008.

[46] Tian, K., Huang, B., Xing, Z., & Hu, W. (2017). Geochemical baseline establishment and ecological risk evaluation of heavy metals in greenhouse soils from Dongtai, China, *Ecological Indicators,* 72, 510-520. doi: 10.1016/j.ecolind.2016.08.037.

[47] Tian, Y., Xu, Y.P., & Wang, G. (2018). Agricultural drought prediction using climate indices based on Support Vector Regression in Xiangjiang River basin. *The Science of the Total Environment*, 622-623, 710-720. doi: 10.1016/j.scitotenv.2017.12.025.

[48] Tse-Tung, M. (2017). Changsha. *Literary Review. Madison: Fairleigh Dickinson University*, 60(3), 24-295.

[49] Welch, R., Pannell, C.W., & Lo, C.P. (1975). Land use in Northeast China, 1973: A view from Landsat-1. *Annals of the Association of American Geographers,* 65, 595-596. doi: 10.1111/j.1467-8306.1975.tb01067.x.

[50] Yan, Y., Ju, H., Zhang, S., & Jiang, W. (2020). Spatiotemporal patterns and driving forces of urban expansion in coastal areas: A study on urban agglomeration in the Pearl River Delta, China. *Sustainability*, 12(1), article number 191. doi: 10.3390/su12010191.

[51] Yao, T., Zhang, X., Guan, H., Zhou, H., Hua, M., & Wang, X. (2018). Climatic and environmental controls on stable isotopes in atmospheric water vapor near the surface observed in Changsha, China. *Atmospheric Environment*, 189, 252-263. doi: 10.1016/j.atmosenv.2018.07.008.

[52] Zhang, J., Mauzerall, D.L., Zhu, T., Liang, S., Ezzati, M., & Remais, J.V. (2010). Environmental health in China: Progress towards clean air and safe water. *Lancet (London, England),* 375(9720), 1110-1119. doi: 10.1016/S0140-6736(10)60062-1.

[53] Zhou, G., & He, Y. (2007). The influencing factors of urban land expansion in Changsha. *Journal of Geographical Sciences,* 17, 487-499. doi: 10.1007/s11442-007-0487-x.

Класифікація земного покриву
та моніторинг процесу урбанізації з використанням знімків Landsat на прикладі міста Чанша, провінція Хунань, Китай

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Анотація. За прогнозами Організації Об'єднаних Націй, до 2050 року 64,1 % країн, що розвиваються, і 85,9 % розвинених країн будуть урбанізованими. Це призвело до швидких змін у землекористуванні та типах земного покриву на територіях навколо міст у всіх країнах, особливо в Китаї, що зумовлює актуальність цієї статті. Метою дослідження було оцінити динаміку змін рослинного покриву в місті Чанша, провінція Хунань, Китай, між 2005 і 2020 роками з використанням часових серій супутникових знімків Landsat і алгоритму класифікації Random Forest. Збір, попередня обробка та аналіз даних проводилися на загальнодоступній онлайн-платформі Google Earth Engine (GEE). Тематичні безперервні растрові карти рослинного покриву були створені за допомогою програмного забезпечення ESRI ArcGIS 10.5.1. Загальна точність класифікації склала понад 83 % для кожної створеної карти, а коефіцієнт Каппа – 0,84 і вище, що підтверджує достовірність результатів класифікації, які за отриманою точністю близькі до аналогічних нещодавніх досліджень. Дослідження показує, що з 2005 по 2020 рік площа густих поселень у місті Чанша, Китай, значно збільшилася, причому експоненціальне зростання міської території склало від 3,23 % до 15,95 %. Частка лісового покриву поступово зменшувалася з 2005 по

2015 рік, але збільшилася з 2015 по 2020 рік. Орні землі були другим найбільш домінуючим типом земельного покриву, з піком майже 50 % у 2010 році. Водні об'єкти залишалися стабільними на рівні близько 3 %. Частка відкритого ґрунту коливалася між 180 і 400 км2 (1,5-3 % від усієї площі). Дослідження показує, що запропонований підхід до моніторингу забезпечує надійні результати, а результати дослідження можуть бути використані для сталого міського планування та управління, а також для ініціатив зі збереження та розвитку. Дані дистанційного зондування та передові ГІС-технології можуть надати особам, які приймають рішення, точні дані для забезпечення сталого розвитку цієї території

Ключові слова: оцінка точності; алгоритм Random Forest; супутникові знімки; загальна точність; урбанізація

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Hedges in Kyiv's public areas and ways to improve them

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Abstract. Green zones in large cities perform important environmental, urban planning, social and economic functions. Hedgerows in the urban greening system are an integral part of ornamental plantings and perform primarily ecological functions. The research aims to analyse hedges growing in public spaces in Kyiv. To achieve this goal, general scientific methods (observation, measurement, and review of scientific literature on the research topic) were used in theoretical and experimental studies. In total, 65689 square metres of the city's hedges, consisting of more than 306 thousand plants and represented by 31 taxa growing on 217 public facilities and maintained by ten district communal enterprises for the maintenance of green spaces of the Kyivzelenbud communal association, were studied. Species composition, height, planting pattern and quality of hedges were analysed. The results showed that the largest number of hedges was created in the

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Solomianskyi and Darnytskyi districts of the city, respectively, 17% and 16% of the total. The most common plant species in hedges is the common privet (*Ligustrum vulgare* L.). The surveyed hedges are mainly created according to single-row and double-row planting schemes in approximately equal proportions. By height group, low hedges predominate, accounting for 53.9% of the total, and medium hedges – 33%. The quality condition is mostly good and satisfactory, which indicates compliance with cultivation techniques and timely maintenance. The results of these studies will allow the balance holders of the facilities with hedges to better organise the agrotechnical work on their arrangement and maintenance in a proper decorative state

Keywords: hedges; functions of hedges; landscaping element; urban environment; urban landscaping, ecology

Introduction

Hedgerows as an element of spatial zoning of the territory of settlements are a multifunctional highly decorative tool for solving several problems related to the separation and protection of certain areas from others, masking objects, creating microclimatic conditions in certain areas, engineering protection, directing pedestrian and vehicle traffic, etc.

The research relevance is predefined by the rapid development of Kyiv's buildings, the increase in the number of harmful substances emitted by vehicles and the need to provide scientifically based recommendations for the development and improvement of the existing condition of hedges to increase their decorative appeal and achieve maximum environmental effect in the modern urban environment of the capital of Ukraine.

One of the biggest problems in a modern metropolis is air quality, with pollution being an inevitable result of a large city's life. Following the official portal of the city of Kyiv (Air quality..., 2018), the concentration of hazardous substances has increased rapidly over the past 20 years, namely nitrogen dioxide by 50% and formaldehyde by 200%. The main reason for these changes is the increase in private vehicles in a constantly developing city. K. Yalovyi (2021) noted that 85% of emissions in the city of Kyiv are caused by mobile sources – of transport, of which 70% are accounted for by private vehicles, a similar situation in the cities of the European Union (Ejdys & Lasota, 2022). A study by K.V. Myronchuk & M.P. Kurnytska (2021) predicted that the increase in private vehicles in the capital by 2025 will be 60% of the officially registered 1.2 million cars as of 2021. Around 50% of emissions come from roads with low speeds. Along with air pollution from harmful emissions, the issue of dust concentration arises, with dust concentration in a typical urban environment being 0.1-0.2 mg/m^3, and in large cities it is at least 0.5 mg/m^3. Another factor that negatively affects urban residents is noise. It is known that a person can withstand a constant noise level of 20-25 dB without any health consequences. V.P. Kucheriavyi & V.S. Kucheriavyi (2022) argued that the main sources of noise in large cities are also roads that exceed the regulatory noise level.

Hedgerows are important elements of landscaping in the modern urban space, especially those along the main transport routes of the city. V.Ya. Zayachuk (2014) noted that they perform important functions, in particular: environmental, urban planning, social and economic. When researching hedges, the ecological function is prioritised. K. Hashad *et al.* (2023), T. Blanusa *et al.* (2019) noted the ability of plants forming hedges to clean the air from pollutants, absorb dust, reduce noise, absorb carbon dioxide, enrich the air with oxygen and, in some cases, the phytoncidal properties of certain plant species, regulate the microclimate, stabilise humidity and temperature, reduce stormwater runoff and the load on the urban sewerage system. H.B. Hladun & H.Yu. Hladun (2013), and O.I. Drebot (2019) found that one hectare of protective green spaces reduces overall air pollution by 10-35%, reduces carbon dioxide concentration by 70%, and provides a 10-15% decrease in temperature in the area adjacent to the carriageway. With the right use of hedges and a reasonable selection of plants, hedges become an integral part of improving the quality of life of metropolitan residents in the context of improving environmental well-being. A.I. Kushnir & O.A. Sukhanova (2022) proved that related functions allow for improving the architectural and planning structure of the city, contribute to the creation of a positive visual perception of the city, increase the cost of housing, create a sense of connection with nature in the centre of an urbanised area, etc. It should be noted that following the provisions of the state building codes (SBR V.2.3-218-007:2012..., 2012), environmental protection must be considered in the design and construction of new roads and highways.

The research aims to examine the existing hedges in public spaces in Kyiv and to develop scientifically based recommendations for the widespread introduction of this type of green space in Kyiv's garden and park facilities.

Materials and Methods

The study was based on existing hedges arranged in public spaces, on roadsides and at transport interchanges in Kyiv. The green fund of the capital consists of 128 parks with an area of 3394.02 hectares, 618 squares (456.53 hectares), 31.6 thousand hectares of urban forests in the buffer zone, 49 boulevards (150 hectares), squares and other green spaces (Website of the Kyivzelenbud..., 2022).

A total of 217 sites with hedges were surveyed in 2022. The study used general methods of scientific knowledge: observation, measurement (inventory of green spaces, assessment of the quantitative and qualitative condition of plantings, statistical processing of identified taxa, study of specific conditions of the place of growth with the greatest harmful factors) and theoretical methods: a review of scientific literature on the research topic, the study of the experience of leading European countries. The assessment of the qualitative state of plants in hedges was carried out following the regulatory recommendations of the Instruction on the inventory of green spaces in cities and urban-type settlements of Ukraine (Order of the Ministry..., 2007) according to the following grades *good condition* – plants are normally developed, dry branches are absent, the hedge is dense, there are leaves along the entire length of the shoots, no obvious mechanical damage, no pests or diseases were found; *satisfactory condition* – bushes are normally developed with signs of slow growth, shoots are exposed, leaves are few, there are mechanical damages and damage by pests and pathogens; *unsatisfactory* – plants are weakened, overgrown, significantly bare, especially in the lower part, many dry branches, mechanical damage and damage by pests and diseases, the general appearance is unattractive.

Results and Discussion

Following the research results, it was found that the total length of hedges in public spaces in ten administrative districts of Kyiv is 65689 linear metres and includes 306257 plant units (Table 1).

Table 1. The total length of hedges in public areas of Kyiv by administrative districts

District name	Number of facilities with hedges	Number of plants in hedges, pcs.	Length of hedges, metres
Holosiivskyi	22	22311	5440.8
Darnytskyi	27	51476	10698
Desnyanskyi	24	37371	6270
Dniprovskyi	24	39325	6525
Obolonskyi	31	13578	3396.9
Pecherskyi	3	47615	9189
Podilskyi	14	20467	5032
Svyatoshynskyi	6	10455	2131
Solomyanskyi	46	43148	11270
Shevchenkivskyi	20	20511	5736
Total:	217	306257	65688.7

Source: compiled by the authors

In general, planting plants in the form of hedges is used in all administrative districts of the capital, but their ratio is not proportional. This is primarily due to the lack of clear standards and recommendations on the need to use hedges in the city's greening system. Separate municipal greenery maintenance enterprises with the status of a legal entities are responsible for the maintenance and development of green spaces in each of the districts, but the decision to install hedges on certain objects is made by different specialists based on their views and considerations (Fig. 1).

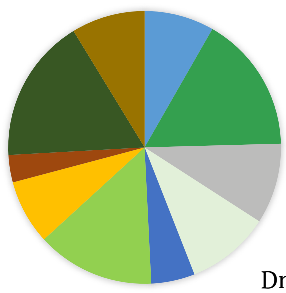

Figure 1. Percentage distribution of the total length of hedges by administrative districts of Kyiv
Source: compiled by the authors

The studied hedges arranged in Kyiv's garden and park facilities are represented by 30 plant taxa, and the most common species is the common privet (*Ligustrum vulgare* L.). The total number of plants of this species is 164680 and accounts for 54% of the total number of planted plants (Table 2). According to the authors, the use of common privet to create hedges is fully justified based on the botanical properties of this plant, as they maximise the ecological function of this type of planting (Kuznetsov *et al.*, 2020; Myronchuk & Henyk, 2021; Ghafari *et al.*, 2020). Quite common plant species for creating hedges in Kyiv are common hornbeam (*Carpinus betulus* L.) 24373 units (8%), Wangutta's hemlock (*Spiraea x vanhouttei* L.) 22248 pcs. (7%), shiny cotoneaster (*cotoneaster lucidus* Schlecht.) 19397 pcs. (6%), common ninebark (*Physocarpus opulifolius* L.) 14594 pcs. (5%), common box (*Buxus sempervirens* L.) 13999 pcs. (5%), Щhite dogwood (*Cornus alba* L.) 10416 pcs. (3%), the other 24 species account for 12% of the total number of plants used, and the percentage of each species is less than 2%.

Table 2. Taxonomic description of Kyiv hedges

No.	Plant name		Amount	
	English	Latin	pcs.	%
1	Wild privet	*Ligustrum vulgare* L.	164680	53.77
2	European hornbeam	*Carpinus betulus* L.	24373	7.96
3	Vanhoutte spirea	*Spiraea x vanhouttei* L.	22248	7.26
4	shiny cotoneaster	*Cotoneaster lucidus* Schlecht.	19397	6.33
5	Common ninebark	*Physocarpus opulifolius* L.	14594	4.77
6	Common box	*Buxus sempervirens* L.	13999	4.57
7	White dogwood	*Cornus alba* L.	10416	3.40
8	Japanese meadowsweet	*Spiraea japonica* L.	5905	1.93
9	Norway maple	*Acer platanoides* L.	5871	1.92
10	Common snowberry	*Symphoricarpos albus* L.	4663	1.52
11	Common lilac	*Syringa vulgaris* L.	3320	1.08
12	Japanese spiraea	*Spiraea bumalda* L.	2900	0.95
13	Philadelphus coronarius	*Philadelphus coronarius* L.	3046	1.00
14	Common dogwood	*Cornus sanguinea* L.	1476	0.48
15	Common barberry	*Berberis vulgaris* L.	1365	0.45
16	Deutzia scabra	*Deutzia scabra* L.	1305	0.43
17	Pyracantha angustifolia	*Pyracantha angustifolia* L.	1168	0.38
18	Ulmus	*Ulmus carpinifolia* Rupp. ex Shchkow	1116	0.36
19	Arborvitae	*Thuja occidentalis* L.	1108	0.36
20	European forsythia	*Forsythia europaea* L.	744	0.24
21	Cornelian cherry	*Cornus mas* L.	510	0.17
22	Amur maple	*Acer ginnala* L.	414	0.14
23	Potentilla intermedia	*Potentilla intermedia* L.	400	0.13
24	Honey locust	*Gleditsia triacanthos* L.	274	0.09
25	Ginkgo	*Ginkgo biloba* L.	264	0.09
26	Common hazel	*Corylus avellana* L.	240	0.08
27	Silver berry	*Elaeagnus angustifolia* L.	180	0.06
28	Guelder-rose	*Viburnum opulus* L.	156	0.05
29	Savin juniper	*Juniperus sabina* L.	75	0.02
30	Mountain currant	*Ribes alpinum* L.	50	0.02
Total			**306257**	**100.0**

Source: compiled by the authors

The second most used species as hedges in Kyiv is the common hornbeam, which is very easy to use and can reach a considerable height. By its characteristics, this species allows for the formation of dense hedges, and since this plant is slow growing, the cost of routine maintenance (mowing) is reduced. When creating hedges, it is necessary to choose already formed seedlings of the required size (Myronchuk, 2014; Dudyn, & Levus, 2022). For example, a hedge made of common hornbeam was arranged in 2018 during the overhaul of the park "Defenders of Ukraine" in the Solomianskyi district. The 4.29-hectare park is located between Vinnytska, Ernsta, S. Khoroboho streets and Povitroflotskoho Avenue (Fig. 2). A 1.8 m high moulded hedge with a total length of 705 metres frames the park along its perimeter, creating a natural screen of protection from high traffic areas. When creating this hedge, 2115 large-sized seedlings were used, which were planted in a two-row planting scheme. It is natural to use the common hornbeam only in 4 districts of Kyiv (Solomianskyi, Sviatoshynskyi, Holosiivskyi and Pecherskyi), as the species is relatively picky about soil fertility. It should be noted that Obolonskyi and left-bank districts of Kyiv have worse soil conditions, as they have mostly sandy, poor soils, and this species is not used there.

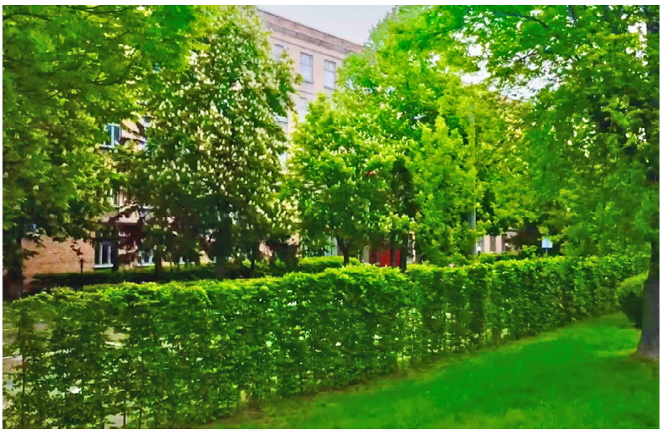

Figure 2. Hedge in the Park of the Defenders of Ukraine

Source: compiled by the authors

As a species widely used as a component of Kyiv's hedges, Vangutta hemlock accounts for 7.26% (22248 specimens) of the total number of taxa used in their creation. The species differs from the previously mentioned species in that it does not require systematic formation and is much less demanding on soil fertility and moisture. Vangutta tawny has a good decorative effect during flowering (Rohovskyi, 2013; Kushnir *et al.*, 2020;). The most widespread distribution of this species is in the Dnipro district of the capital, where 9068 plants were found, creating 1447 metres of linear hedges in the Peremoha Park, along A. Malyshko Street, near the Aurora Cinema, in the park at 5 Vershyhora Street, in the park at Berezniakivska Street, at the transport interchange of Alisher Navoi Street, etc. The height of the Vangutta hedges is 0.6-1.0 m.

Shiny cotoneaster, common ninebark and white dogwood occupy a significant place in hedges. When studying the plantings in Maksym Shapoval Park in the Solomianskyi district, a hedge with a combination of decorative forms (cultivars) of the common ninebark by leaf colour (yellow and purple) was found, which has a significant decorative effect.

Common box hedges are quite problematic in terms of maintenance in public areas. To date, 2883 linear metres of hedges have been created from this species. They are arranged mainly in the central districts of the city. The largest number of them was recorded in the Pechersk district on Lesia Ukrainka Boulevard – 1750 linear metres. Undoubtedly, boxwood has the greatest decorative effect throughout the year, but it requires constant care, including the use of chemical pest control agents, suffers greatly and reproduces relatively slowly after mechanical damage, suffers from animal urine burns, and is often stolen by social unaware layers of the population (Shukel, 2011). Given the above, we do not recommend the use of boxwood in public places.

The main technology of hedges in Kyiv is a single-row and double-row planting scheme (Fig. 3).

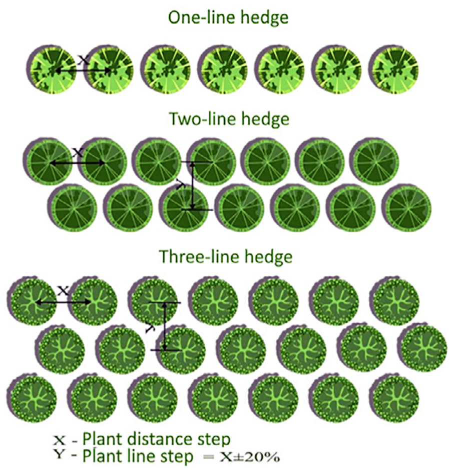

Figure 3. Hedge scheme

Source: compiled by the authors

Mostly, 3 plants per linear metre of single-row hedges are planted and 5 plants per linear metre of double-row hedges (Table 3). In some cases, hedges arranged by a three-row planting scheme were noted, but their number is insignificant and was not considered in the general analysis of field studies.

As a result of the research, an almost equal ratio of single-row and double-row hedges in public areas in the context of the city of Kyiv was established (43.7% and 56.3%, respectively), but if we analyse these indicators within individual administrative districts, we get contradictory results. For example, most hedges in Podilskyi and Pecherskyi districts are created according to a single-row planting scheme, while in Darnytskyi and Obolonskyi districts the situation is the opposite, and in Sviatoshynskyi district single-row planting was not used at all. This indicates the absence of a citywide standard or scientific and practical recommendations in the field of green economy for planting hedges. Given the above, we state that the leading function of hedges is precisely the environmental one, and therefore standardisation in this area, according to the authors, is timely and necessary (Dworniczak & Reda, 2021; Borowski *et al.*, 2021).

When analysing hedges by height, four groups were identified: borders (up to 0.5 m high), low hedges 0.5-1.0 m high, medium hedges 1.0-2.0 m high, and high hedges above 2.0 m high. The results are shown in Table 4.

Table 3. Analysis of the applied hedge planting scheme

District name	**overall hedge length**			
	one-line		**two-line**	
	long meter	**%**	**long meter**	**%**
Holosiivskyi	2182	40.1	3258.8	59.9
Darnytskyi	1007	9.4	9691	90.6
Desnyanskyi	1669.6	26.6	4600.4	73.4
Dniprovskyi	2722	41.7	3803	58.3
Obolonskyi	390.2	11.5	3006.66	88.5
Pecherskyi	7853	85.5	1336	14.5
Podilskyi	4823	95.8	209	4.2
Svyatoshynskyi	0	0.0	2131	100.0
Solomyanskyi	5950.3	52.8	5319.7	47.2
Shevchenkivskyi	2126.65	37.1	3609.35	62.9
Overall in Kyiv	**28723.75**	43.7	**36964.91**	56.3

Source: compiled by the authors

Table 4. Distribution of hedges by height

District name	**Length of hedges, long metres**			
	up to 0.5m	**0.5-1.0m**	**1.0-2.0m**	**over 2.0m**
Holosiivskyi	0	2238.8	2236	866
Darnytskyi	0	8345.6	2349	0
Desnyanskyi	2011.9	4010.1	188	0
Dniprovskyi	379	4001	2145	0
Obolonskyi	402.66	2404.23	559.97	0
Pecherskyi	1750	6103	0	1336
Podilskyi	282	3016	1734	0
Svyatoshynskyi	40	70	2021	0
Solomyanskyi	558	4257.6	5062	862.3
Shevchenkivskyi	82	941.1	5376.75	0
Overall in Kyiv	5505.56	35387.43	21671.72	3064.3
%	8.4	53.9	33.0	4.7

Source: compiled by the authors

Thus, most hedges in public areas of Kyiv belong to the group of low hedges (53.9%), the second place with an indicator of 33% is occupied by medium-height hedges, the participation of curbs and high hedges, respectively, is 8.4% and 4.7%. The data obtained quite logically confirm the intention of landscaping specialists regarding the further maintenance and care of these elements of green infrastructure, as most of the surveyed hedges are moulded. In terms of maintenance, tall hedges are much more expensive to maintain, and curbs mostly do not play an ecological role and are only a decorative element. Based on the recommendations of the Instruction on the Inventory of Plantations in Cities and Urban Areas of Ukraine (Order of the Ministry…, 2007) their species composition, length in metres, type of planting (single-row and double-row) and assessment of their quality condition were described (Fig. 4).

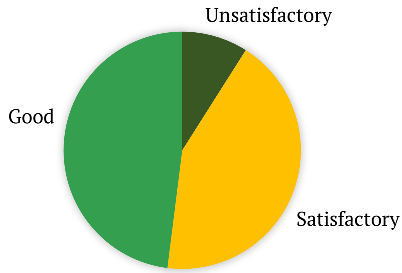

Figure 4. Quality of hedges in public areas of Kyiv

Source: compiled by the authors

Most of the inspected hedges at the garden and park facilities of the city of Kyiv are in good condition. The plants in the hedges are well maintained, and they are constantly cared for following the requirements of agricultural practices. Some hedges have minor mechanical damage, some pest damage, and partial exposure of shoots in the lower part and are classified as in satisfactory condition. According to the inspection, only 9% of hedges were classified as unsatisfactory, mostly old plantings that need reconstruction and replacement.

The research results on the species composition and structure of hedges in the urban environment are currently insufficiently covered in the works of Ukrainian and foreign scientists. For example, in the green areas of Chernivtsi, the most used species are boxwood, white boxwood, common privet, and medium-sized meadowsweet (Myronchuk & Henyk, 2021). In another study, researcher K.V. Myronchuk (2014) analysed the patterns of creation and condition of hedges in rural and urban areas of Bukovyna and found that in cities, curbs, single-row hedges consisting of one species predominate, and in non-urban areas, taller hedges, mostly combined, are prevalent, usually using common hornbeam, white privet, and evergreen boxwood. Similar in species composition to the hedges in Chernivtsi are the hedges in Mukachevo, where evergreen boxwood, white pigweed, and common privet are mostly used for this type of planting (Dudyn, & Levus, 2022). Similarly, to the green areas of public use in Kyiv, the study by A.A. Dzyba & A.V. Baikovska (2015) found that similar plantations in Kharkiv are characterised by the predominance of privet. The most common in the public areas of this city are formed single-row hedges of deciduous woody plant species, while borders and living walls are less common. As in the above cities, the hedges of Lutsk are characterised by the predominance of medium-height hedges created using such plants as black cotoneaster, Vangutta hemlock, common privet, white privet, and viburnum (Shukel, 2011).

The results of several studies on the creation and maintenance of hedges in European cities have revealed both differences and similarities concerning hedges in Ukrainian cities.

For example, S.V. Rohovskyi (2013) points out the frequent use of Pyracantha charlatanica in the creation of hedges, which is not typical for the Ukrainian cities under study. At the same time, the formation of hedges in the cities of Vienna, Budapest, Krakow, and Prague is similar, with the use of evergreen boxwood, common privet, cotoneaster brilliant, hornbeam, white snowberry, Wangutt's hemlock, and Thunberg's barberry. The dominant plants that create hedges in the city of Swidnik (Poland) are shiny irga, common privet and plum alder (Muras & Frazik-Adamczyk, 2002; Lubiarz & Kulesza, 2012). The studies of C. Farrell *et al.* (2022) revealed an ecological approach to the selection of an assortment of plants, including hedges, for use in Australian urban landscapes. It is worth noting that the analysed studies on the peculiarities of creating and maintaining hedges in European cities note their highly decorative state and unsurpassed appearance, which is achieved through regular professional care. To improve and develop hedges in Ukrainian cities, the main components are to increase the level of agrotechnical measures, reconstruction, rejuvenation, and replacement of old hedges, as well as a reasonable approach to the choice of planting material, which is proposed by domestic scientists in the above studies.

Conclusions

Based on the research conducted on the condition of hedges in the system of landscaping public spaces in Kyiv, the following conclusions can be drawn:

1. Hedgerows account for a significant proportion of the city's garden and park facilities. Their length is 65689 linear metres, and the number of plants is more than 306 thousand.

2. The hedges are in good and satisfactory condition, which indicates that they are systematically maintained by the specialists of the district greenery maintenance companies.

3. The studied hedges are represented by 30 plant taxa. The most widespread species is the common privet (*Ligustrum vulgare* L.), which accounts for 54% of the total number of planted plants. Other common plant species are common hornbeam (*Carpinus betulus* L.) – 8%, Wangutta's hemlock (*Spiraea x vanhouttei* L.) – 7%, shiny cotoneaster (*cotoneaster lucidus* Schlecht.) – 6%, common ninebark (*Physocarpus opulifolius* L.) – 5%, common box (*Buxus sempervirens* L.) – 5%, White dogwood (*Cornus alba* L.) – 3%, and the remaining 24 species account for only 12%.

4. To improve the condition of hedges, it is necessary to develop a targeted programme for the development of this type of planting as part of the capital's environmental development plan.

5. Hedgerows are important in the urban greening system, and therefore we recommend their wider use, especially in places directly adjacent to recreation areas to transport routes, along pedestrian sidewalks, on boulevards and transport interchanges.

6. The selection of planting material for hedges should be scientifically based, considering the main objectives and economic factors for their further maintenance.

The authors believe that the use of hedges in garden and park facilities is one of the most promising ways to develop urban green infrastructure in Ukrainian settlements. They allow for solving global issues of improving the ecological state, improving the comfort of the inhabitants of the urban environment, and enhancing the aesthetic perception of cities in general. The prospect of further research is to study the state of hedges in other Ukrainian cities.

Conflict of Interest

The authors declare no conflict of interest.

Acknowledgements

None.

References

[1] Air quality research is being conducted in Kyiv. (2018). Retrived from https://kyivcity.gov.ua/news/u_kiyevi_provoditsya_doslidzhennya_yakosti_atmosfernogo_povitrya/.

[2] Blanusa, T., Garratt, M., Cathcart-James, M., Hunt, L., & Cameron R.W.F. (2019). Urban hedges: A review of plant species and cultivars for ecosystem service delivery in north-west Europe. *Urban Forestry & Urban Greening*, 44, article number 126391. doi: 10.1016/j.ufug.2019.126391.

[3] Borowski, J., Czarny, P., Krynicki, M., Motas, M., Stolarczyk, J., Wodzicki, R., Tyszko-Chmielowiec, P., & Witkoś-Gnach, K. (2021). *Standard cięcia i pielęgnacji drzew*. Wrocław: Fundacja EkoRozwoju.

[4] Drebot, O.I. (2019). The influence of forest strips on the ecological condition of road transport lands. *Balanced Natue Using*, 4, 26-34. doi: 0.33730/2310-4678.4.2019.

[5] Dudyn, R.B., & Levus, T.M. (2022). Ecological and biological bases of hedge formation in Mukachevo city. *International Scientific Journal "Grail of Science"*, 17, 196-199. doi: 10.36074/grail-of-science.22.07.2022.034.

[6] Dworniczak, Ł., & Reda, P. (2021). *Standard ochrony drzew i innych form zieleni w procesie inwestycyjnym*. Wrocław: Fundacja EkoRozwoju.

[7] Dzyba, A.A., & Baikovska A.V. (2015). The current state of hedges in public spaces in Kharkiv. *Scientific Bulletin of the National University of Life and Environmental Sciences of Ukraine,* 229, 141-147.

[8] Ejdys, S., & Lasota, F. (2022). Protection of the environment in terms of functioning of urban transport. Literature review. *Rocznik Ochrona Srodowiska,* 24, 481-492. doi: 10.54740/ros.2022.034.

[9] Farrell, C., Livesley, S.J., Arndt, S.K., Beaumont, L., Burley, H., Ellsworth, D., Esperon-Rodriguez, M., Fletcher, T.D., Gallagher, R., Ossola, A., Power, S.A., Marchin, R., Rayner, J.P., Rymer, P.D., Staas, L., Szota, C., Williams, N.S.G., & Leishman, M. (2022). Can we integrate ecological approaches to improve plant selection for green infrastructure? *Urban Forestry & Urban Greening,* 76, article number 127732. doi: 10.1016/j.ufug.2022.127732.

[10] Ghafari, S., Kaviani, B., Sedaghathoor, S., & Allahyari, M.S. (2020). Ecological potentials of trees, shrubs and hedge species for urban green spaces by multi criteria decision making. *Urban Forestry & Urban Greening*, 55, article number 126824. doi: 10.1016/j.ufug.2020.12682.

[11] Hashad, K., Yang, B., Gallagher, J., Baldauf, R., Deshmukh, P., & Zhang, K.M. (2023). Impact of roadside conifers vegetation growth on air pollution mitigation. *Landscape and Urban Planning*, 229, article number 104594. doi: 10.1016/j.landurbplan.2022.104594.

[12] Hladun, H.B., & Hladun, H.Yu. (2013). Protection of highways by forest plantations of the linear type and their projected volumes. *Forestry and Agroforestry,* 123, 103-113.

[13] Kucheriavyi, V.P., & Kucheriavyi, V.S. (2021). *Landscaping of populated areas*. Lviv: "Novyi Svit-2000".

[14] Kushnir, A.I., & Sukhanova, O.A. (2022). *Agrotechnics of plants in landscape construction* (Part I. Coniferous trees). Kyiv: IEYamchynskyi.

[15] Kushnir, A.I., Pushkar, V.V., Sukhanova, O.A., & Vakulyk, I.I. (2021). *Encyclopedic dictionary-reference book of landscaper*. Kyiv: CP "COMPRINT".

[16] Kuznetsov, S.I., Kushnir, A.I., Levon, F.M., Pushkar, V.V., Sukhanova, O.A., Kuznetsova, M.S., & Honcharenko, B.V. (2020). *Assortment of trees, shrubs and vines for landscape construction in Ukraine*. Kyiv: CP "COMPRINT".

[17] Lubiarz, M., & Kulesza, P. (2012). Znaczenie przyrodnicze i krajobrazowe zywoplotow przy ciagach komunikacyjnych w Swidniku (Woj. Lubelskie). *Teka Komisji Architektury, Urbanistyki i Studiow Krajobrazowych*, VIII/2, 50-60.

[18] Muras, P., & Frazik-Adamczyk, M. (2002). *Zywoploty*. Krakow: Plantpress.

[19] Myronchuk, K.V. (2014). Comparative characteristics of models of hedge creation and formation in rural and urban areas (on the example of Chernivtsi region). *Scientific Bulletin of the National Forestry University of Ukraine*, 24.8, 78-82.

[20] Myronchuk, K.V., & Henyk, Ya.V. (2021). Composition, ecological structure and decorative effect of hedges in the urban environment of Chernivtsi. *Scientific Bulletin of the National Forestry University of Ukraine*, 31(5), 47-53. doi: 10.36930/40310507.

[21] Myronchuk, K.V., & Kurnytska, M.P. (2021). Dust protection function of hedges on the example of urban ecosystems of the Chernivtsi region. *Scientific Bulletin of the National Forestry University of Ukraine*, 31(4), 48-53. doi: 10.36930/40310407.

[22] Official Website of the Kyivzelenbud Municipal Association. (n.d.). Retrived from http://kyivzelenbud.com/about/strategiya-rozvytku.

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

[24] Rohovskyi, S.V. (2013). Experience in maintaining green spaces in European cities and its use in Ukraine. *Scientific Bulletin of the National University of Life and Environmental Sciences of Ukraine*, 187(1), 126-134.

[25] SBR V.2.3-218-007:2012. (2012). *Environmental requirements for highways*. Designing. Kyiv: State Highway Agency of Ukraine (Ukravtodor).

[26] Shukel, I.V. (2011). Hedges in Lutsk city and methods of their improvement. *Scientific Bulletin of the National Forestry University of Ukraine*, 21.16, 331-335.

[27] Yalovyi, K. (2021). *Caution: The air! 12 facts about what Kyiv residents breathe*. Retrived from http://kyivzelenbud.com/about/strategiya-rozvytku.

[28] Zayachuk, V.Ya. (2014). *Dendrology*. Lviv: SPOLOM.

Живоплоти в місцях загального користування міста Києва та шляхи їх вдосконалення

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Анотація. Зелені насадження урбанізованого середовища великих міст виконують важливі екологічні, містобудівельні, соціальні та економічні функції. Живоплоти в системі озеленення мегаполісу є невід'ємною частиною декоративних насаджень та виконують насамперед екологічні функції. Метою роботи було провести аналіз живих огорож, що зростають в насадженнях загального користування міста Києва. Для досягнення поставленої мети під час теоретичних, експериментальних досліджень використовувалися загальнонаукові методи (спостереження, вимірювання, огляд наукової літератури по темі дослідження). Загалом досліджено 65689 м.п. живих огорож міста, що складаються з понад 306 тис. рослин та представлені 31 таксонами, які зростають на 217 об'єктах загального користування і знаходяться на обслуговуванні десяти районних комунальних підприємств по утриманню зелених насаджень комунального об'єднання «Київзеленбуд». Проаналізовано видовий склад, висоту, схему посадки та якісний стан живих огорож. За результатами встановлено, що найбільша кількість живих огорож створено у Солом'янському та Дарницькому районах міста, відповідно, 17 % і 16 % від загальної кількості. Самим розповсюдженим видом рослин у складі живоплотів є бирючина звичайна (*Ligustrum vulgare* L.). Обстежені живі огорожі створені переважно за однорядною та дворядною схемами посадки приблизно у рівних співвідношеннях. За групою висот переважають низькі живоплоти, кількість яких становить 53,9 % від загальної, середніх за висотою – 33 %. Якісний стан переважно добрий та задовільний, що свідчить про дотримання агротехніки вирощування та своєчасності догляду. Результати цих досліджень на практиці дозволять підприємствам-балансоутримувачам об'єктів із зростаючими на них живоплотами краще організувати проведення агротехнічних робіт щодо їх влаштування і утримання в належному декоративному стані

Ключові слова: живі огорожі; функції живих огорож; елемент озеленення; урбанізоване середовище; міське озеленення; екологія

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Current state and productivity of Scots pine modal stands of the Forest Steppe of Ukraine

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Abstract. The development of regulatory and reference support for the inventory assessment of the state of modal stands is an urgent issue, since it allows obtaining reliable and up-to-date information on the current state of existing forests. The purpose of the study was a statistical substantiation of the division of pine stands into groups by region of growth and stand composition,

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and their detailed inventory characteristics with an analysis of the distribution in the Forest-Steppe and their productivity. To conduct the study, a stand-wise database of the Production Association "Ukrderzhlisproekt" for Forest-Steppe zone of Ukraine was used. Using a number of non-parametric criteria for evaluating samples (Kruskal-Wallis one-way analysis of variance, the median criterion, Jonckheere-Terpstra test), the study established a difference in the stands parameters of the samples under study and divided the stands of the Forest-Steppe zone into four groups. The main task was to describe the current state of modal pine stands of the Forest-Steppe zone of Ukraine for selected groups, with a detailed distribution of areas and stocks according to the main stand parameters According to the results of the database analysis, it was found that about 92% of the total area of pine stands of the Forest-Steppe zone are artificial forests. Depending on the region of growth, the stands were divided into the left- and right-bank parts of the Forest-Steppe, in composition – into pure and mixed stands. Within the groups under study, the distribution of areas and stocks of pine stands was analysed according to site index classes, types of forest-growing conditions, forest types, relative stand density, and age groups. Site index classes in all groups are dominated by high site index stands of I and I[a] site index classes. The proportion of high-grade mixed stands is greater compared to pure stands. In terms of the forest-growing conditions, stands in condition B_2 dominate in all groups under study. From the left bank to the right bank, there is an increase in soil fertility from condition B to condition C, and this dependence is also observed from pure to mixed stands. Productivity in terms of the average growing stock of mixed stands of the right-bank and left-bank parts of the Forest-Steppe is very close and considerably less than the stocks of pure stands. The presented research results can be used by scientists as a description of the modal inventory characteristics of the Forest-Steppe region and for the grouping of experimental data when compiling forestry and forest inventory standards

Keywords: stand-wise database; non-parametric criteria; average growing stock; site index; stand species composition; site condition; relative stand density

Introduction

The improvement of the system of information support for the inventory assessment of forest resources of Ukraine is a significant issue that requires a detailed investigation, estimation, description, and development of relevant normative and reference support to assess the condition and forecast the growth of the main forest-forming tree species, considering the specific features of their growth depending on the region, forest-growing conditions, origin, and composition. An important stage of research is to establish, for a particular tree species, which stands by origin and composition are the most common in a given region for the subsequent compilation of growth charts for modal stands.

Scots pine (*Pinus sylvestris* L.) occupies the largest share of forests in Ukraine, they make up over 33%, or 3,130 thous. ha of forest areas covered with forest vegetation (Lovynska *et al.*, 2021). Scots pine stands are found in all natural areas of Ukraine. Such a wide area is explained by the unpretentiousness of this tree species to the temperature regime, the ability to withstand significant frosts up to -50 °C, soil – up to -24 °C, and heat – up to +40 °C. Scots pine is one of the key species in Europe and extends from the boreal region of Northern and Eastern

Europe to the Mediterranean mountains of Southeastern Europe (Socha *et al.*, 2021). Scots pine belongs to xerophytic and oligotrophic tree species, and therefore it can grow both on poor-fertility sands and on rich chernozems, it can be found even on stony soils, in the steppe zone and swamps.

Pine forests play a vital ecological role, namely, water protection, water regulation, soil protection, and anti-erosion. Pine stands regulate surface runoff, protect soil from erosion, and water sources from pollution, which is especially important on the sandy soils of Polissia (Yukhnovskyi *et al.*, 2021). Given the unpretentiousness of pine to soils, it is often used in the afforestation of anthropogenically disturbed landscapes (Brovko *et al.*, 2021), ravines and gullies, on poor and eroded soils, and can also be the main species in the afforestation of old arable land (Lakyda *et al.*, 2011). The ability of pine to release a considerable amount of volatile phytoncides has ensured its widespread use for recreational and sanitary purposes. On the territory of Ukraine, there are a significant number of health facilities located directly in pine forests.

Pine timber is important for the national economy of the country, especially widely used in construction, suitable for the manufacture of ore risers necessary for the development of mineral deposits. The presence of resinous substances provides increased resistance of wood to rot and has the property of creaking when the load increases, which is useful for labour protection of miners.

It was important to investigate the statistical substantiation of the possibility of grouping data on the Forest Fund, which will later be used as source data, into homogeneous groups. It is necessary to statistically confirm the similarity or difference between stands of different tree species in composition and origin. Pine stands of Ukraine are mostly concentrated in the Polissia zone (73.3% of the area of all pine stands (Bala *et al.*, 2017)) and a considerable number of scientific forestry studies, including forest inventory studies, have been devoted to their investigation, while the study of the growth of pine stands in the Forest Steppe of Ukraine has received less attention. Of the currently available ones, studies of pine stands in the Forest-Steppe were conducted mainly on its left-bank part. This can be explained by the territorial location of the H.M. Vysotsky Ukrainian Research Institute of Forestry and Agroforestry (Kharkiv), whose scientists addressed various silvicultural problems of pine stands. Thus, at different times, studies of the productivity of pine stands on the left bank of the Forest-Steppe were conducted by O.V. Tovstukha (2012), V.V. Nazarenko & V.P. Pasternak (2016), V.Yu. Yarotsky *et al*. (2016), V.P. Tkach *et al*. (2018), A.V. Harmash (2019) and S.I. Musienko *et al*. (2021) investigated the current state of pine stands within the left-bank Forest-Steppe of Ukraine and their age structure. The study of radial increment and the influence of climate changes on it is described in the studies of researchers I.M. Koval *et al.* (2018), I.M. Koval & V.O. Voronin (2019), O.A. Mikhaylichenko *et al.* (2021). V.P. Chigrinets *et al.* (2012) investigated forestry issues of the typological structure of pine forests of the left-bank Forest-Steppe, O.M. Tarnopilska & O.A. Ponomarev (2008) examined the impact of forestry measures, namely maintenance felling of various intensities, on their growth. The vast majority of these studies concerned Scots pine stands growing in the Kharkiv and Sumy regions. Some studies were limited to the territory of separate forestry enterprises.

The purpose of this study was statistical confirmation or refutation of the null hypothesis about the significance of the difference between the average stand parameters in modal pine stands of the Forest-Steppe zone of Ukraine in terms of groups of stands differing in growth region, origin, and composition, as well as determining the groups according to which further forest inventory standards for modal Scots pine stands should be compiled and their detailed inventory characteristics.

The main tasks were to conduct a detailed analysis of the growing stands of Scots pine on the territory of the Forest-Steppe of Ukraine; to determine the main groups according to growth region (left or right bank of the Forest-Steppe), origin (artificial or natural) and composition (pure or mixed) for further statistical and inventory research; to conduct a statistical comparison of the selected groups on the subject of similarity or difference in their stand parameters; to describe the current state of modal pine stands of the Forest-Steppe zone of Ukraine for selected groups with a detailed distribution of areas and stocks according to the main stand parameters.

Materials and Methods

The calculations were performed using the sub-compartment forest inventory data of the database of the Production Association (PA) "Ukrderzhlisproekt" for the forest-growing zone of the Forest-Steppe with a division into groups according to the composition and origin of the tree stands (Ukrainian State Project..., n.d.). Stands of all departmental subordinations involving Scots pine in the stand composition of 2 or more units were selected for analysis. Therewith, almost 95% of all tree stands consisted of 6 or more units of Scots pine. Before using the database, it was verified to search for and filter out gross errors in the analysed inventory features of tree stands. As a result, an array of 133,540 forest stands with a total area of 451.3 thous. ha was used for further work.

For further statistical process ing, the database was divided into four groups:

1. artificial pure stands of the right-bank part of the Forest-Steppe, with 10 units of the main species in the stand composition (hereinafter – PR);
2. artificial pure stands of the left-bank part of the Forest-Steppe, with 10 units of the main species in the stand composition (hereinafter – PL);
3. artificial mixed stands of the right-bank part of the Forest-Steppe, with less than 10 units of the main species in the stand composition (hereinafter – MR);
4. artificial mixed stands of the left-bank part of the Forest-Steppe, with less than 10 units of the main species in the stand composition (hereinafter – ML).

The distributions of age, average height, average diameter, density, and average stock per 1 ha were used for statistical processing of samples.

The study was based on the principles of a system approach using modern information technologies and software (program for statistical data processing – IBM SPSS Statistics). During the study, general scientific (analysis, synthesis, hypothesis) and special (forestry, inventory, biometric) methods of cognition were combined. Analysis and synthesis were used to process, analyse, and group input information from the forest inventory characteristic database. The hypothesis was used to predict the division of experimental material into groups in the context of the stand composition and geographical location. Forestry methods in combination with inventory methods were used to group and analyse experimental data by types of forest conditions and average parameters of stands. Biometric methods were used in statistical data processing and calculation of criteria for estimating sample similarity.

Considering the data of previous studies (Bala *et al.*, 2019), namely the difference of the distribution of forestry information from the normal distribution, as well as the possibility of simultaneous comparison of several groups under study, it was decided to use non-parametric methods. Non-parametric methods that allow comparing the level of expression of a variable include Kruskal-Wallis one-way analysis of variance (Kruskal, 1952); criterion of medians (Friedlin & Gastwirth, 2000); Jonckheere-Terpstra criterion of ordered alternatives (Jonckheere, 1954).

The Kruskel-Wallace test is used to assess differences between the groups under study with medians and is a generalization of the Mann-Whitney *U*-test (Mann & Whitney, 1947) for two independent samples. Thus, the Kruskel-Wallace test is a non-parametric alternative to the *F*-test in univariate analysis of variance and uses the total variance when comparing two independent samples (Agresti, 2019). If the conditions necessary for the application of the *F*-test in univariate analysis of variance are met, the Kruskel-Wallace test has analogous capabilities. The Kruskel-Wallace test is used to test the hypothesis about the equality of the medians of independent samples that belong to the same general population.

The median criterion is a non-parametric statistical criterion that belongs to the class of rank bias criteria. It allows testing the hypothesis that the shape of the distributions of two samples is identical and that there is a difference between them by a certain constant value (Friedlin & Gastwirth, 2000). Therewith, the total median is calculated for all independent samples, after which the number of measured values that are larger or smaller than the median is calculated. The result is the construction of a field table containing 2·k fields, which is then subjected to a chi-square test. In general, the median criterion is not very effective.

The Jonckheere-Terpstra criterion for ordered alternatives is a better alternative to the Kruskel-Wallace criterion, in the case when the samples under study are naturally ordered. Important is not only the fact that there are differences between several samples, but also the direction of change (increase or decrease) of differences when moving from sample to sample. To solve problems of this type, the Jonckheere-Terpstra criterion is used with an alternative hypothesis: “there are differences between samples, and the medians of samples are arranged in ascending order”. To use this criterion, samples must be ordered according to the expected growth of the factor effect (e.g., average values). The Jonckheere-Terpstra criterion allows for a more detailed analysis and often reveals differences in cases where the Kruskel-Wallace criterion is ineffective (Bala *et al.*, 2019).

Using the above methods in the present study, hypothesis testing matrices were constructed, which allowed determining the similarity of the tree stands under study and identifying homogeneous groups of stands according to their composition and geographical location.

During the study of the distribution of pine stands according to the type of forest-growing conditions (FGCT), the scale of P.S. Pogrebnyak (1955) was used, according to which plots are divided according to soil fertility and denoted by the letters A, B, C, and D from poor to rich in terms of fertility. In addition, an index is added to the letter that characterizes soil moisture and is indicated by numbers from 0 to 5, where 0 is very dry, and 5 is very wet growing conditions.

Results and Discussion

Analysis and modelling of stand parameters of modal stands of Scots pine in the Forest-Steppe of Ukraine requires a clear division of the latter into statistically substantiated homogeneous structural elements (groups), which further allows finding adequate models to predict their growth and development, identify natural factors of influence on the growth and development of tree stands, and reduce the variance of input research data. For this, the special stand-wise database provided by PA “Ukrderzhlisproekt” (Ukrainian State Project…, n.d.) was analysed, which characterizes Scots pine stands that differ in composition and origin. As a result, the distribution of the areas of the stands under study according to these parameters was obtained (Table 1). Pure stands included stands with 10 units of the main species in the stand composition, which was substantiated in the study of P.I. Lakyda *et al.* (2012).

Table 1. Distribution of Scots pine stands in the Forest-Steppe of Ukraine

Origin	Composition	Forest-Steppe natural area							
		left-bank				right-bank			
		area		total stock		area		total stock	
		ha	share	thous. m^3	share	ha	share	thous. m^3	share
Natural	Pure	10448.3	60.1	3471.69	65.4	8464.2	42.8	2633.94	44.9
	Mixed	6951.0	39.9	1837.39	34.6	11320.6	57.2	3226.65	55.1
	Total	17399.3	7.2	5309.08	7.1	19784.8	8.0	5860.59	8.7
Artificial	Pure	172402.3	76.7	56484.83	81.5	134026.6	59.2	39297.79	64.0
	Mixed	52290.4	23.3	12842.49	18.5	92559.3	40.8	22119.47	36.0
	Total	224692.7	92.8	69327.32	92.9	226585.9	92.0	61417.26	91.3
Total		242092.0	100.0	74636.4	100.0	246370.7	100.0	67277.9	100.0

Source: developed by the authors based on data (Ukrainian State Project..., n.d.)

Scots pine stands in the Forest-Steppe of Ukraine cover an area of 488,462 thous. ha and have a total stock of 141.914 million m^3 (Table 1). They are distributed almost evenly in the left-bank and right-bank parts (49.6% in the left-bank and 50.4% in the right-bank part of the areas of pine stands of the Forest-Steppe). Therewith, these stands are mainly of artificial origin. Thus, in the left-bank part of the Forest-Steppe, the share of artificial stands is 92.8% (224,692 thous. ha) of the area of pine stands in the left-bank part; for the right-bank part, this figure is 92% (226,586 thous. ha), respectively. Considering the small share of natural tree stands, it was decided to conduct further analysis for artificial tree stands. The share of artificial pure stands in the composition in the left-bank part is quite high and amounts to 172,402 thous. ha (76.7% of the area of artificial pine stands in the left-bank part of the Forest-Steppe); for the right-bank part, this figure is 134,027 thous. ha (59.2%).

The groups under study were compared using the statistical methods described above, and the null hypothesis about the similarity of the compared groups was accepted. In the obtained results, the *p*-value of the calculated indicator exceeds 0.001, which proves the existence of a relationship between the stand parameters of the groups under study and confirms their similarity. In addition, in comparison diagrams of calculated values, the equidistance of points from each other indicates that there is no relationship between the stand parameters of the groups under study.

The results of hypothesis testing using various methods are presented in Table 2.

Table 2. Result of testing hypotheses about sample equality

Stand parameters	Criteria for independent samples	Result
Age	Median criterion	Hypothesis rejected
	Kruskal-Wallace test	Hypothesis rejected
	Jonckheere–Terpstra test	Hypothesis rejected

Table 2, Continued

Stand parameters	Criteria for independent samples	Result
Average height	Median criterion	Hypothesis rejected
	Kruskal-Wallace test	Hypothesis rejected
	Jonckheere–Terpstra test	Hypothesis rejected
Average diameter	Median criterion	Hypothesis rejected
	Kruskal-Wallace test	Hypothesis rejected
	Jonckheere–Terpstra test	Hypothesis rejected
Relative density	Median criterion	Hypothesis rejected
	Kruskal-Wallace test	Hypothesis rejected
	Jonckheere–Terpstra test	Hypothesis rejected
Stock per 1 ha	Median criterion	Hypothesis rejected
	Kruskal-Wallace test	Hypothesis rejected
	Jonckheere–Terpstra test	Hypothesis rejected

Source: compiled by the authors

An example of paired comparisons of the median criterion is presented in Figure 1. Thus, the data in Table 2 and Figure 1 demonstrate that for all comparison groups, the null hypothesis of sample similarity is not confirmed by statistical criteria and should be rejected. Further analysis should be carried out for the groups under study, which factor in their statistical differences.

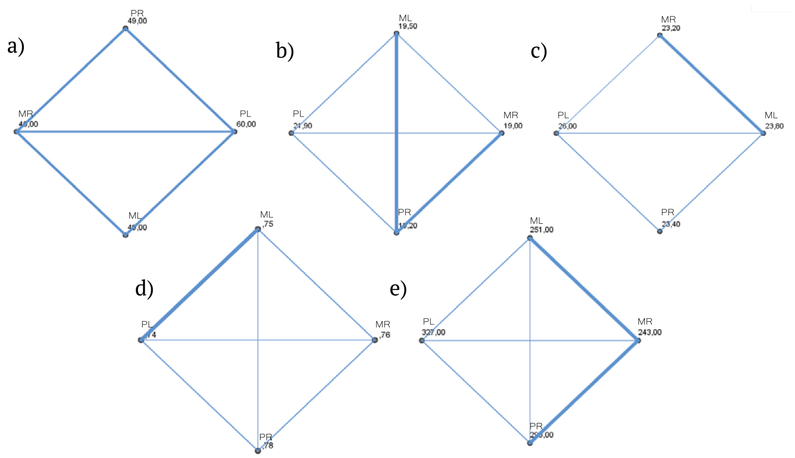

Figure 1. Comparison diagrams for the values of paired criteria for the median stands of Scots pine: a) age, b) average height; c) average diameter; d) density, e) stock per 1 ha

Source: compiled by the authors

Based on data from the stand-wise database, average stand parameters for artificial pine stands were calculated by groups according to natural zones and composition. The obtained parameters are presented in Table 3.

Table 3. Average stand parameters of artificial pine stands in the Forest-Steppe of Ukraine

Forest-Steppe natural area	Composition	Age, years	Height, m	Diameter, cm	Relative density	Stock, $m^3 \cdot ha^{-1}$
Left-bank	Pure	60	20.6	25.3	0.74	310
	Mixed	48	17.8	22.4	0.74	235
	Total	57	19.8	24.6	0.74	290
Right-bank	Pure	51	18.7	23.4	0.76	284
	Mixed	46	17.6	22.4	0.75	232
	Total	49	18.2	22.9	0.76	262
Total		53	19.1	23.8	0.75	276

Source: developed by the authors based on data (Ukrainian State Project..., n.d.)

The data in Table 3 suggests that the pine stands of the left-bank part of the Forest-Steppe of Ukraine are older compared to the stands of the right-bank part, and their age is 57 years and 49 years, respectively. Notably, pure tree stands are older than mixed ones throughout the Forest-Steppe. Analysing the data in the table, it should be noted that the average stand parameters of the pine stands of the left bank part are higher than the corresponding parameters of the stands of the right-bank part, such results can primarily be explained by the different age structure, which could affect the difference in parameters. Pure stands are characterized by greater productivity than mixed ones, the average stock per 1 ha for the left-bank part is 310 m^3 and for the right-bank part – 284 m^3.

The distribution of pine stand areas according to site index classes is presented in Table 4 and Figure 2.

Table 4. Distribution of areas of pine stands in the Forest-Steppe of Ukraine according to site index classes

Composition	Site index	Forest-Steppe natural area					
		left-bank			right-bank		
		area		stock, $m^3 \cdot ha^{-1}$	area		stock, $m^3 \cdot ha^{-1}$
		ha	share		ha	share	
Pure	I^c and above	265.7	0.2	360	384.7	0.3	357
	I^b	6041.1	3.5	396	5546.0	4.1	370
	I^a	43348.4	25.1	366	40737.5	30.4	348
	I	84000.8	48.7	309	60270.9	45.0	276
	II	28732.1	16.7	262	21108.3	15.7	211
	III	7404.4	4.3	184	4986.6	3.7	144
	IV and below	2609.8	1.5	129	992.6	0.7	97
	Total	172402.3	100.0		134026.6	100.0	
Mixed	I^c and above	285.0	0.5	336	514.4	0.6	299
	I^b	4217.3	8.1	347	6823.7	7.4	311
	I^a	15808.0	30.2	300	33016.7	35.7	289
	I	23708.1	45.3	201	38030.3	41.1	201
	II	6573.5	12.6	172	11005.6	11.9	152
	III	1376.9	2.6	117	2803.3	3.0	99
	IV and below	321.6	0.6	96	365.3	0.4	64
	Total	52290.4	100.0		92559.3	100.0	

Source: developed by the authors based on data (Ukrainian State Project..., n.d.)

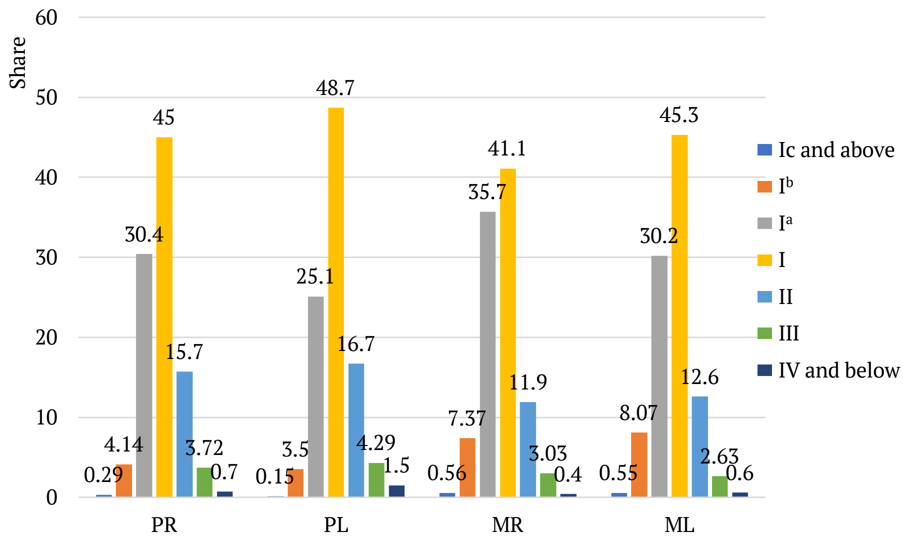

Figure 2. Distribution of pine stand areas according to site index classes

Source: developed by the authors based on data (Ukrainian State Project…, n.d.)

The above data suggests that the share of tree stands that grow according to site index class I and higher, pure stands of the left-bank part of the Forest-Steppe is 77.5% (133,656 thous. ha, from the area of pure Scots pine stands of the left-bank part of the Forest-Steppe). For the right-bank part of the Forest-Steppe, this figure was 79.8% (106,939 thous. ha). Notably, the proportion of high-purity mixed stands is higher compared to pure stands. Thus, the share of mixed stands with high site index class of the left-bank part of the Forest-Steppe is 84.2% (44,018 thous. ha, from the share of mixed Scots pine stands of the left-bank part of the Forest-Steppe), for the mixed stands of the right-bank part of the Forest-Steppe, this share was 84.7% (78,385 thous. ha). The average site index class of mixed stands for both regions is I^a, 7; for the left-bank part, pure stands have an average site index class I,0, for the right-bank part – I^a, 9.

According to the type of forest-growing conditions for different groups, pine stands in the Forest-Steppe of Ukraine are distributed unevenly (Table 5 and Fig. 3). Specifically, 19.5% (33,619 thous. ha of the area of pure pine stands of the left-bank part of the Forest-Steppe) of pure pine forests of the left-bank part are distributed in conditions A, 61.9% (105,943 thous. ha) – in conditions B, 17.8% (30,732 thous. ha) – in conditions C and D. Mixed pine stands of the left-bank part grow in richer forest-growing conditions, the share of growth in conditions C and D was 46.2% (24,147 thous. ha of the area of mixed pine stands of the left-bank part of the Forest-Steppe), the share of pine growth in conditions B – 45.6% (23,854 thous. ha) and conditions A – 7.6% (3,996 thous. ha). Mixed pine stands of the right-bank part of the Forest-Steppe are common in much richer forest-growing conditions than others. Thus, the share of growth conditions C and D was 64.8% (59,940 thous. ha, from the area of mixed pine stands in the right-bank part of the Forest-Steppe), the share of conditions B – 27.2% (25,177 thous. ha) and conditions A – 2.5% (2,321 thous. ha). Pure pine stands of the right-bank part of the Forest-Steppe were distributed as follows: A – 10.6%; B – 44.4%; C and

D – 42.6%. According to the analysis results, the following dependence of Scots pine growth in the Forest-Steppe is observed: in the left-bank part, poorer conditions B dominate; on the right bank, from pure to mixed stands, there is a change in growth from conditions B to conditions C; in all areas, fresh growth conditions predominate in terms of humidity (index 2).

Table 5. Distribution of areas and stocks of pine stands in the Forest-Steppe of Ukraine according to types of forest-growing conditions (FGCT)

FGCT	Forest-Steppe left-bank zone				Forest-Steppe right-bank zone			
	pure		mixed		pure		mixed	
	area, ha	stock, $m^3 \cdot ha^{-1}$	area, ha	stock, $m^3 \cdot ha^{-1}$	area, ha	stock, $m^3 \cdot ha^{-1}$	area, ha	stock, $m^3 \cdot ha^{-1}$
A_1	6,529.8	182	571.5	147	3,955.7	170	294.2	83
A_2	27,089.2	259	3,424.6	157	10,310.8	246	2,026.6	128
B_1	1,776.9	259	272	181	5,104.8	248	999.1	139
B_2	105,008.4	324	22,804.9	218	50,943.5	303	22,003.2	212
B_3	934.9	350	776.6	243	3,485.6	246	2,174.5	202
C_2	27,579.9	333	20,085.4	262	42,158.7	299	39,042.6	243
C_3	1,833.3	370	1,966.4	286	4,480.3	321	8,126.9	252
D_2	1,319.2	297	2,095.1	269	10,506.6	260	12,770.8	242
Other FGCTs	330.7	210	293.9	165	3,080.6	232	5,121.4	230
Total	172,402.3		52,290.4		134,026.6		92,559.3	

Source: developed by the authors based on data (Ukrainian State Project..., n.d.)

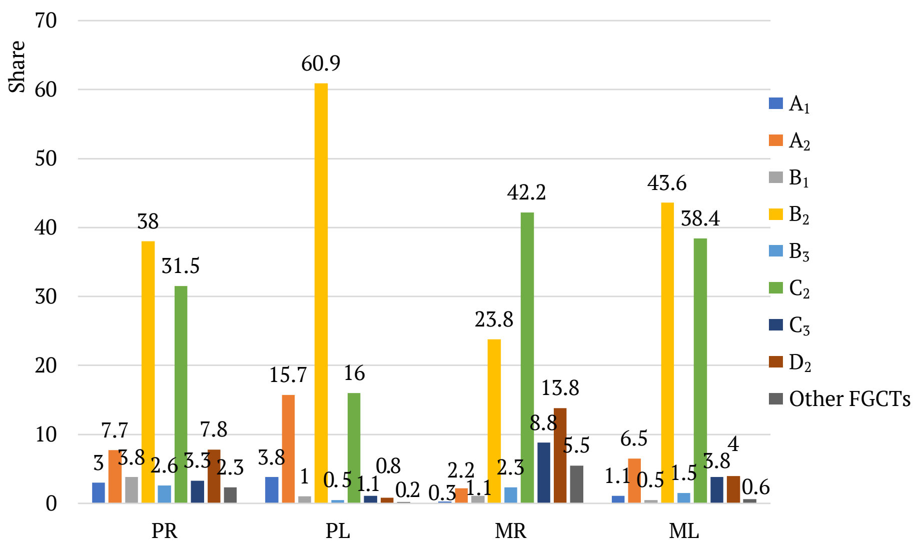

Figure 3. Distribution of areas of pine stands in the Forest-Steppe of Ukraine according to types of forest-growing conditions

Source: developed by the authors based on data (Ukrainian State Project..., n.d.)

Analysing the average stock of pine stands, the greatest productivity in terms of stock in all groups is observed in conditions C_3. The largest margin in pure stands: 370 $m^3 \cdot ha^{-1}$ for the left-bank part and 321 m³·ha⁻¹ for the right-bank part. Mixed stands in these conditions have an average margin for the left-bank part of 286 $m^3 \cdot ha^{-1}$, and for the right-bank – 252 $m^3 \cdot ha^{-1}$.

Over 86% of the area of pine stands in the Forest-Steppe of Ukraine has a relative completeness of 0.7-0.9 (Table 6 and Fig. 4). There is a difference in the distribution of relative stand density for the left- and right-bank parts of the Forest-Steppe, there is no significant difference in the distribution of tree stands for pure and mixed stands. In general, pine stands of the right-bank part are described by a higher proportion of high-density stands (with a density of 0.9-1.0) and, accordingly, a lower proportion of stands with a density of 0.7. There is also a share of stands (up to 14%), which grow with a reduced density of 0.6 and below. The most productive according to average margin are stands with a density of 0.9 for all groups of pine stands.

The age structure of stands is not uniform (Table 7 and Fig. 5). The share of young ani-

Table 6. Distribution of areas and stocks of pine stands in the Forest-Steppe of Ukraine according to relative stand density

Density classes	Forest-Steppe left-bank zone				Forest-Steppe right-bank zone			
	pure		mixed		pure		mixed	
	area, ha	stock, $m^3 \cdot ha^{-1}$	area, ha	stock, $m^3 \cdot ha^{-1}$	area, ha	stock, $m^3 \cdot ha^{-1}$	area, ha	stock, $m^3 \cdot ha^{-1}$
0.4 and under	1,375.9	175	392.9	142	833.5	140	503.0	136
0.5	3,681.1	226	1,365.0	162	2,675.9	197	1,793.0	173
0.6	17,591.5	283	5,111.1	188	11,493.7	240	7,907.0	202
0.7	59,712.8	314	16,930.0	231	37,621.6	266	27,018.1	215
0.8	66,494.3	320	21,273.9	251	53,577.7	297	39,483.3	249
0.9	22,695.1	329	6,826.8	272	27,049.2	317	15,155.5	254
1.0	851.6	249	390.7	254	775.0	263	699.4	196
Total	172,402.3		52,290.4		134,026.6		92,559.3	

Source: developed by the authors based on data (Ukrainian State Project..., n.d.)

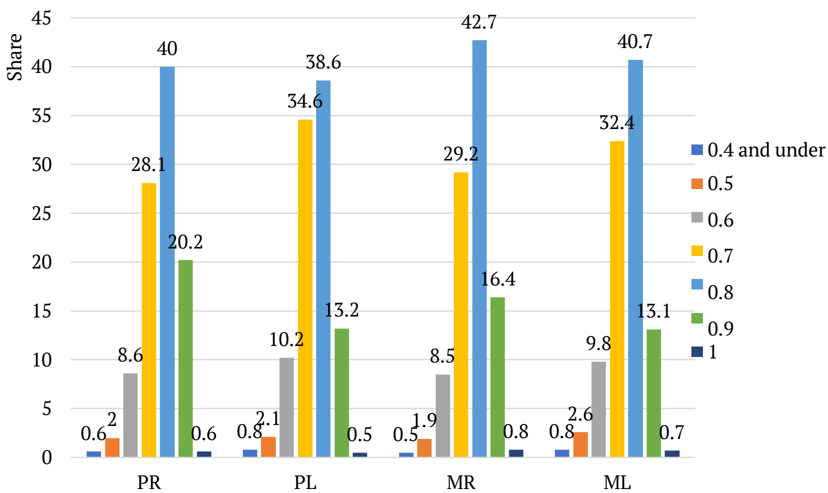

Figure 4. Distribution of areas of pine stands in the Forest-Steppe of Ukraine according to relative stand density

Source: developed by the authors based on data (Ukrainian State Project..., n.d.)

mals in pure pine stands of the left-bank part of the Forest-Steppe is 20.13 thous. ha (11.7% of the area of pure pine stands of the left-bank part), a considerable share of middle-aged stands –115.823 thous. ha (67.2%) and mature 30.742 thous. ha (17.8%) and a small area of mature and over-mature stands 5,663 thous. ha (3.3%). Mixed stands of the left-bank part of the Forest-Steppe are described by a large share of young animals – 35.7% (18,659 thous. ha) of the area of mixed stands of the left-bank Forest-Steppe and, accordingly, smaller shares of middle-aged stands (47.6% or 24,873 thous. ha) and maturing (13.9% or 7,289 thous. ha) and a small share of mature and over-mature 2.8% (1,469 thous. ha). In contrast to the pure pine stands of the left-bank part, the stands of the right-bank part have a large share of young animals, which make up 25.2% of the area of pure pine stands of the right-bank part of the Forest-Steppe (33,714 thous. ha), a considerable share of middle-aged – 61.2% (81,984 thous. ha) and maturing – 10.6% (14,152 thous. ha) as well as for other stands, the share of mature and over-mature is insignificant – 2.8% (1,469 thous. ha). The largest part of young animals is observed in mixed stands of the right-bank part of the Forest-Steppe, their share is 40.2% (37,216 thous. ha) of the area of mixed stands of the right-bank Forest-Steppe. The share of middle-aged stands is 47.5% (44,003 thous. ha) and maturing stands – 9.1% (8,449 thous. ha). The share of mature and over-mature stands is 2.8% (2,890 thous. ha).

Table 7. Distribution of areas and stocks of pine stands in the Forest-Steppe of Ukraine according to age groups

Age group	Forest-Steppe left-bank zone				Forest-Steppe right-bank zone			
	pure		mixed		pure		mixed	
	area, ha	stock, $m^3 \cdot ha^{-1}$	area, ha	stock, $m^3 \cdot ha^{-1}$	area, ha	stock, $m^3 \cdot ha^{-1}$	area, ha	stock, $m^3 \cdot ha^{-1}$
Young	20,173.0	127	18,658.7	95	33,714.2	152	37,216.4	106
Middle-aged	115,823.2	330	24,873.4	302	81,983.5	324	44,003.3	305
Maturing	30,742.3	388	7,289.1	367	14,152.4	401	8,449.4	373
Mature	5,593.9	385	1,458.0	358	4,137.3	374	2,863.1	344
Over-mature	69.9	317	11.2	298	39.2	314	27.1	339
Total	172,402.3		52,290.4		134,026.6		92,559.3	

Source: developed by the authors based on data (Ukrainian State Project..., n.d.)

Figure 6 shows the dynamics of the average stock for the researched groups of pine stands in the Forest-Steppe of Ukraine.

Analysing the dynamics of stock changes per 1 ha (Fig. 6), it should be noted that the most productive stands are pure Scots pine stands in the right-bank part of the Forest-Steppe. Therewith, starting from the age group of the mature ones, there is a decrease in the stock on average from 388 to 317 $m^3 \cdot ha^{-1}$. The productivity of pure pine stands of the left-bank part of the Forest-Steppe is lower than the stock of pure stands of the right-bank part, in the age group, mature and over-mature stocks per 1 ha exceed pure stands of the right-bank part. In general, the stocks of mixed stands in the right-bank and left-bank parts of the Forest-Steppe are very close and significantly less than the stocks of pure stands. Notably, a decrease in stocks after the maturing age group is observed for all groups of stands.

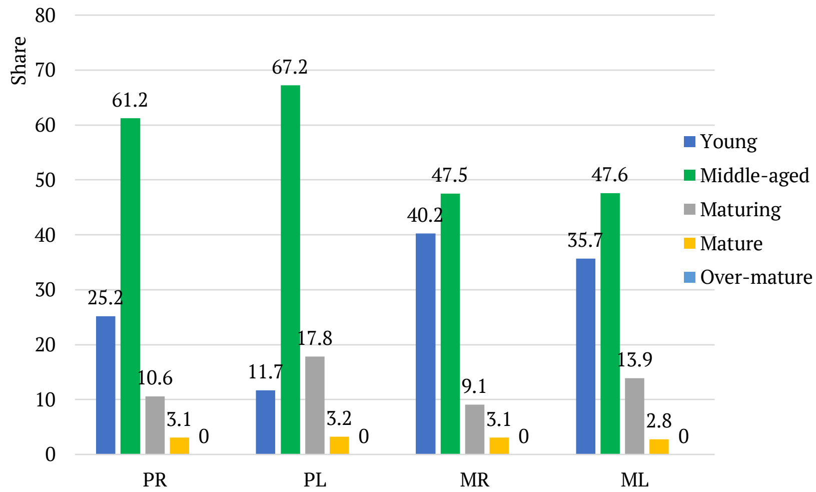

Figure 5. Distribution of areas of pine stands in the Forest-Steppe of Ukraine according to age groups

Source: developed by the authors based on data (Ukrainian State Project..., n.d.)

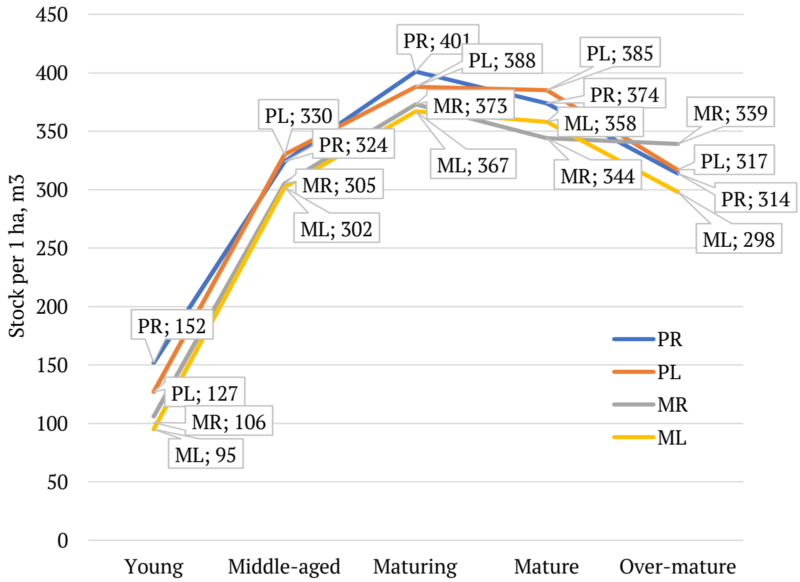

Figure 6. Dynamics of the average stock of pine stands in the Forest-Steppe of Ukraine

Source: developed by the authors based on data (Ukrainian State Project..., n.d.)

To verify the conducted research, we will compare it with the data obtained by other scientists. As mentioned earlier, scientists paid little attention to Scots pine stands in the Forest-Steppe of Ukraine, so we compared the dynamics of changes in the average stock per 1 ha with the data of S. Musienko *et al.* (2021) for the left-bank part of the Forest Steppe, as well as with collective studies of natural pine stands of Polissia (Lakyda *et al.*, 2018) and the Northern Steppe of Ukraine (Lovynska *et al.*, 2021). In their research, the authors determined the productivity of pine stands without dividing them into pure and mixed ones, so we present the data for both of these groups. The results obtained are presented in Table 8 and Figure 7.

Table 8. Average stock per 1 ha of pine stands in the left-bank part of the Forest-Steppe

Age classes	Average stock per 1 ha, m^3				
	pure stands	mixed stands	according to S. Musienko *et al.* (2021)	according to (Lakyda *et al.*, 2018) for Polissia	according to (Lovynska *et al.*, 2021) for the Northern Steppe
I	14	14	13	11	9
II	57	48	47	30	31
III	128	109	115	67	99
IV	209	183	210	109	160
V	272	256	296	167	242
VI	323	307	331	251	270
VII	354	343	352	298	313
VIII	383	363	384	323	360
IX	388	366	389	324	376
X	358	336	378	313	356
XI	374	350	336	286	366
XII	363	365	321	279	363
XIII	342	340	276	-	-
XIV	346	293	260	-	-
XV and above	289	289	250	-	-

Source: developed by the authors based on (Lakyda *et al.*, 2018; Lovynska *et al.*; 2021; Musienko *et al.*, 2021; Ukrainian State Project...,n.d.)

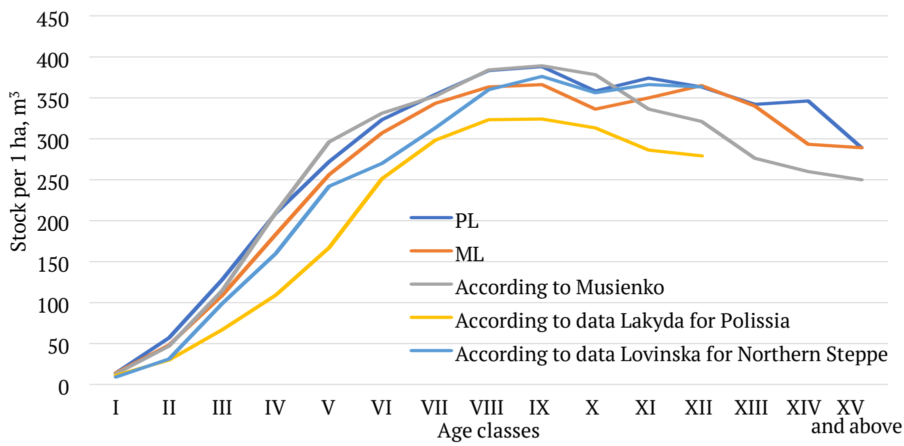

Figure 7. Dynamics of the average stock of pine stands in the left-bank part of the Forest-Steppe of Ukraine

Source: developed by the authors based on (Lakyda *et al.*, 2018; Lovynska *et al.*; 2021; Musienko *et al.*, 2021; Ukrainian State Project...,n.d.)

According to the presented data, in general, the dynamics of stocks per 1 ha of the compared data is close to the pure tree stands of the left-bank part of the Forest-Steppe of Ukraine. This is also confirmed by the average value of Scots pine presence in stands – 9.7 units. After the IX age class, there is a significant decrease in the average stock per 1 ha according to S. Musienko's data, which can be explained by the small area of the researched object (State Enterprise "Zhovtneve Forestry") and the specific features of forestry activities. For the conditions of the Northern Steppe (Lovynska *et al.*, 2021), the average stock per 1 ha is slightly lower than the stocks for the Forest-Steppe zone. Therewith, in the VIII class of age, they increase sharply and correspond to the stocks of the Forest-Steppe zone, which is explained by the presence of such stands mainly in the composition of protective stands of green zones and sanitary zones and their insignificant representation. In addition, the productivity of natural pine stands of Polissia is significantly less than in the Forest-Steppe and Steppe.

Conclusions

As a result of the conducted study, forest inventory dependencies were established that characterize the growth of Scots pine stands in the Forest-Steppe zone of Ukraine. In the research of Ukrainian scientists, when investigating the growth of Scots pine stands, preference is given to stands growing in the natural zone of Polissia of Ukraine. This is primarily because in these conditions this species is considered as a priority. But in the Forest-Steppe zone, more attention is paid to oak stands. Much less attention is paid to the growth of Scots pine in other natural areas; specifically, studies were conducted for the Forest-Steppe, but were limited exclusively to its eastern part (Kharkiv and Sumy regions). The originality of the conducted study was the coverage of the entire territory of the Forest-Steppe zone of Ukraine using the stand-wise database of PA "Ukrderzhlisproekt". In fact, the provided database is a general set of forest inventory data of stands that include Scots pine growing in the Forest-Steppe zone of Ukraine. Having conducted an initial analysis of the database, it was decided to investigate only artificial Scots pine stands, since they occupy about 92% of the total area of pine stands in the Forest-Steppe of Ukraine. Using several non-parametric statistical criteria to estimate the similarity of samples, the difference in stand parameters of pine stands was established and divided into four groups depending on the geographical location and participation of the main species in the stand composition. The analysis of the groups under study proved that Scots pine on the territory of the Forest-Steppe zone of Ukraine grows relatively evenly within its left-and right-bank parts. Pure tree stands are older than mixed ones and, accordingly, have a higher productivity (about 300 $m^3 \cdot ha^{-1}$ in pure and 235 $m^3 \cdot ha^{-1}$ in mixed stands). However, the highest middle site index class is characterized by mixed stands in both regions, the lowest middle site index class – in pure stands of the left-bank Forest-Steppe. By types of forest vegetation conditions, poorer conditions B dominate in the left-bank part, while on the right bank, from pure to mixed stands, there is a change in growth from conditions B to C. In terms of productivity, pure stands of the right-bank part of the Forest-Steppe of Ukraine dominate. The description and generalization of the current state and analysis of the productivity of pine stands in the Forest-Steppe zone of Ukraine can be used for further grouping of experimental material in the preparation of forestry and forest inventory standards. The obtained description is the most complete since it was based on the entire sub-compartment inventory characteristic of Scots pine stands in the region under study.

Conflict of Interest

The authors declare no conflict of interest.

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None.

References

[1] Agresti, A. (2019). *An introduction to categorial data analysis*. New York: Wiley.

[2] Bala, O.P., & Terentiev, A.Yu. (2017). The modern state and productivity of modal stands of pine and spruce of Ukraine. *Ukrainian Journal of Forest and Wood Science*, 266, 91-104.

[3] Bala, O.P., Terentiev, A.Yu., Lakyda, I.P., & Matushevych, L.M. (2019). Application of some parametric and non-parametric criteria for grouping forests biometric data. *Ukrainian Journal of Forest and Wood Science,* 10(3), 4-18. doi: 10.31548/forest2019.03.004.

[4] Brovko, F.M., Brovko, D.F., Brovko, O.F., & Yukhnovskyi, V.Yu. (2021). Productivity of seedlings of Scots pine on alluvial sands of natural and man-made origin. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, 3, 88-94. doi: 10.33271/nvngu/2021-3/088.

[5] Chigrinets, V.P., Tovstukha, A.V., & Pyvovar, T.S. (2012). Typological structure of pine forests of Sumy region. *Forestry and Forest Melioration*, 121, 57-65.

[6] Friedlin, B., & Gastwirth, J.L. (2000). Should the median test be retired from general use? *The American Statistician*, 54, 161-164. doi: 10.2307/2685584.

[7] Harmash, A.V. (2019). Pine stands of Forest-steppe zone of Kharkiv region: Productivity and natural regeneration. *Forestry and Forest Melioration*, 135, 14-23. doi: 10.33220/1026-3365.135.2019.14.

[8] Jonckheere, A.R. (1954). A distribution-free k-sample test against ordered alternatives. *Biometrika*, 41, 133-145. doi: 10.2307/2333011.

[9] Koval, I.M., & Voronin, V.O. (2019). Response of *Pinus sylvestris* L. radial growth to climate change in stands in left-bank Forest-Steppe. *Forestry and Forest Melioration*, 135, 140-148. doi: 10.33220/1026-3365.135.2019.140.

[10] Koval, I.M., Sydorenko, C.H., & Nevmyvaka, M.O. (2018). Post-pyrogenic development of a young pine plantation in the Forest-Steppe. *Man and Environment. Issues of Neoecology*, 30, 123-129. doi: 10.26565/1992-4224-2019-30.

[11] Kruskal, W.H., & Wallis, W.A. (1952). Use of ranks in one-criterion variance analysis. *Journal of the American Statistical Association*, 260, 583-621.

[12] Lakyda, P.I., Vasylyshyn, R.D., Terentiev, A.Yu., Lashchenko, A.H., & Bala, O.P. (2011). The growth dynamics of modal pine stands created on lands unsuitable for agricultural use. *Scientific Bulletin of the National University of Life and Environment Science of Ukraine. Series: Forestry and Decorative Horticulture*, 164(1), 68-78.

[13] Lakyda, P.I., Terentiev, A.Yu., & Vasylyshyn, R.D. (2012). *Artificial pine stands of Polissia of Ukraine – prognosis of growth and productivity*. Kyiv: IE Maidachenko I.S.

[14] Lakyda, P.I., Vasylyshyn, R.D., Blyshchyk, V.I., Lakyda, I.P., Terentiev, A.Y., Domashovets, H.S., & Sratii, N.V. (2018). *Experimental data on live biomass of Ukrainian coniferous forests*. Kyiv: PC Comprint.

[15] Lovynska, V., Terentiev, A., Lakyda, P., Sytnyk, S., Bala, O., & Gritzan Yu. (2021). Comparison of Scots pine growth dynamic within Polissya and Northern Steppe zone of Ukraine. *Journal of Forest Science*, 67, 533-543. doi: 10.17221/93/2021-JFS.

[16] Mann, H.B., & Whitney, D.R. (1947). On a test of whether one of two random variables is stochastically larger than the other. *Annals of Mathematical Statistics*, 18, 50-60.

[17] Mikhaylichenko, O.A., Ustsky, I.M., Boltenkov, Yu.A., Stovbunenko, D.V., & Shygrynets, V.P. (2012). Condition of second-generation pine cultures in the former arable lands on the left bank of Seversky Donets river. *Forestry and Forest Melioration*, 120, 128-132.

[18] Musienko, S.I., Rumiantsev, M.N., Lukyanets, V.A., Tarnopilska, O.M., Bondarenko, V.V., & Yushchyk V.S. (2021). Sondition and productivity of pine plantations in the Forest-Steppe of Kharkiv region. *Scientific Bulletin of UNFU*, 31(6), 41-47. doi: 10.36930/40310605.

[19] Nazarenko, V.V., & Pasternak, V.P. (2016). *Patterns of formation of forest types of Forest-steppe of the Kharkiv Region*. Kharkiv, KhNAU.

[20] Official website of the Ukrainian State Project Forest Management Industrial Association "Ukrderzhlisproekt". (n.d.). Retrieved from https://www.lisproekt.gov.ua/.

[21] Pogrebnyak, P.S. (1955). *Fundamentals of forest typology*. Kyiv: Academy of Sciences.

[22] Socha, J., Tymińska-Czabańska, L., Bronisz, K., Zięba, S., & Hawryło, P. (2021). Regional height growth models for Scots pine in Poland. *Scientific Reports*, 11, article number 10330. doi: 10.1038/s41598-021-89826-9.

[23] Tarnopilska, O.M., & Ponomarev, O.A. (2008). Influence of selective and linear & selective thinning on forming of pine plantations in the South Forest Steppe. *Forestry and Forest Melioration*, 113, 111-120.

[24] Tkach, V.P., Kobets, O.V., & Rumiantsev, M.G. (2018). Use of forest site capacity by forests of Ukraine. *Forestry and Forest Melioration*, 132, 3-12. doi: 10.33220/1026-3365.132.2018.3.

[25] Tovstukha, O.V. (2012). Age structure of pine forests of SE "Shostka Forest Enterprise". *Forestry and Forest Melioration*, 120, 23-30.

[26] Vedmid, M.M. (2005). To the issue of forest lands potential productivity evaluation. *Forestry and Forest Melioration*, 108, 3-8.

[27] Yarotsky, V.Yu., Pyvovar, T.S., Pasternak, V.P., & Garmash, A.V. (2016). The structure of pine stands at the Left-bank Foreststeppe of Ukraine. *Scientific Bulletin of UNFU*, 26(4), 56-59. doi: 10.15421/40260408.

[28] Yukhnovskyi, V., Polishchuk, O., Lobchenko, G., Khryk, V., & Levandovska, S. (2021). Aerodynamic properties of windbreaks of various designs formed by thinning in central Ukraine. *Agroforestry Systems*, 95, 855-865. doi: 10.1007/s10457-020-00503-8.

Сучасний стан та продуктивність модальних насаджень сосни звичайної Лісостепу України

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Анотація. Розробка нормативно-довідкового забезпечення для таксаційної оцінки стану модальних деревостанів є нагальним питанням оскільки дає можливість отримати достовірну та актуальну інформацію про сучасний стан існуючих деревостанів. Метою роботи було статистичне обґрунтування поділу соснових деревостанів на групи за регіоном зростання та складом, та їх детальна таксаційна характеристика з аналізом поширення на території Лісостепу та їх продуктивності. Для проведення досліджень використовувалась база даних повидільної таксаційної характеристики лісів виробничого об'єднання «Укрдержліспроект» для лісостепової зони України. Використовуючи ряд непараметричних критеріїв оцінки вибірок (ранговий однофакторний *H*-критерій Краскела-Уоллеса, критерій медіан, критерій впорядкованих альтернатив Джонкіра-Терпстра) було встановлено відмінність в таксаційних показниках досліджуваних вибірок та розділено деревостани лісостепової зони на чотири групи. Було описано сучасний стан модальних соснових деревостанів лісостепової зони України для обраних груп з детальним розподілом площ та запасів за основними таксаційними показниками. За результатами проведеного аналізу бази даних було встановлено, що близько 92 % від загальної площі соснових деревостані лісостепової зони становлять штучні ліси. Залежно від регіону зростання – на ліво- та правобережну частину Лісостепу, за складом – на чисті та мішані. В межах досліджуваних груп було проведено аналіз розподілу площ та запасів соснових деревостанів за класами бонітету, типами лісорослинних умов, типами лісу, відносними повнотами та групами віку. За класами бонітету у всіх групах домінують високобонітетні насадження I та I[a] класів бонітету. Частка високобонітетних мішаних насаджень більша в порівнянні з чистими насадженнями. За типом лісорослинних умов домінують насадження B_2 у всіх досліджуваних групах. Із лівобережжя до правобережжя спостерігається зростання родючості ґрунтів із умов B на умови C, також така залежність спостерігається від чистих до мішаних насаджень. Продуктивність за середнім запасом мішаних насаджень правобережної та лівобережної частини Лісостепу дуже близькі і значно менше запасів чистих деревостанів. Наведені результати досліджень можуть бути використані науковцями в якості опису модальних таксаційних характеристик регіону Лісостепу та для групування експериментального матеріалу при складанні лісівничих та лісотаксаційних нормативів

Ключові слова: повидільна база даних; непараметричні критерії; середній запас; клас бонітету; склад насадження; тип лісорослинних умов; відносна повнота

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Terminological basis and perspectives of the use of non-timber products of the forests of Ukraine

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Abstract. In the forests of Ukraine, forestry should be carried out on the principles of continuous and rational use of forests through integrated usage of their resources. Thus, there is a need to distinguish and correctly understand the forestry terms. To harmonize terminology, relevant regulations, as well as Ukrainian and foreign literature, were examined. General scientific theoretical methods – analysis and synthesis – were applied to work with information sources. The paper substantiats the employment and understanding of terminology related to the usage of forest resources. The definition and interpretation of the terms "secondary forest use", "non-tree forest resources", "non-timber forest resources" in current legislative and regulatory acts, the explanatory dictionary of the Ukrainian language, the state standard of Ukraine, the Ukrainian encyclopedia of forestry, Ukrainian and foreign forestry literature were summarized. The authors proposes to divide forest resources into woody, non-tree, and non-timber ones, followed by coordination of such classification among forestry scientists and practitioners. The largest volumes of harvesting

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among secondary forest materials and secondary forest uses for 2010-2020 were established. The distribution of income received according to types of non-timber products of the forest and in the context of regional departments of forestry and hunting for 2021 was analysed. The paper presents the types of wild fruit, medicinal plants and mushrooms common in Ukraine. Promising species for plantation cultivation were proposed. Areas of obtaining added income from the sale of non-timber products of forests were generalized. The analysis and prospects of using non-timber forest products, which can serve as a theoretical and practical basis for sustainable management of multifunctional forestry in Ukraine, were presented. The obtained results can be used for harvesting non-timber products of forests, considering the regional characteristics of the country

Keywords: wild fruits; medicinal plants; mushrooms; birch sap; legislative and regulatory documents

Introduction

The forest resources of Ukraine are extremely diverse in their species composition and nature of use. Apart from timber, other products are also harvested in the forests. People have used forests as a source of food and medicinal products for a long time. The beginning of primitive people's usage of forest resources was the gathering of fruits, mushrooms, medicinal herbs, etc. Subsequently, forest resources were used for the construction of housing, fences, making household utensils and tools. Resin was extracted and processed by people as early as the 3rd century BC, and tree sap was produced on an industrial scale at the beginning of the 20th century (Tokarieva *et al.*, 2022).

At the end of the 19th century, the term "resources (products) of secondary forest use" appeared in the scientific literature in Ukraine. The term "non-tree forest products" is now a commonly adopted in Ukraine. According to C.M. Shackleton & A. de Vos (2022), wild forest products have currently various names, but the most common in the world literature is non-timber forest products.

A system of terms and definitions specified by current regulations, standards, instructions in Ukraine is covered in encyclopaedic publications. The terminology concerning the harvesting of secondary forest materials and the implementation of secondary forest uses, that has been translated from Soviet literature is inaccurate and requires clarification. Therefore, it is often difficult to understand their essence, since there are different approaches to describing the resource system, and the definitions of the terms "non-tree" and "non-timber" forest resources have no scientific substantiation.

T.S. Delgado *et al.* (2016) noted that traditionally forest resources were interpreted only as timber stock, and forest policy focused on the use of forests mainly as suppliers of timber. I. Grammatikopoulou & D. Vačkářová (2021) emphasized the social significance of non-timber products in forests. According to A.V. Myhal & V.V. Bokoch (2017), with the increasing importance of other useful products and functions of the forest, its resources began to include secondary forest products and materials.

Multifunctional forestry is a relevant and modern area of forestry development and one of the main concepts that guide the European community (Pohjanmies *et al.,* 2021; Romabai *et al.*, 2022). Despite of widespread acceptance of the general concept, there is a lack of consistency in terminology definitions, forest policies in this area, and communication between practitioners. M.A. Hoogstra-Klein *et al.* (2017) concluded that it was important to match different practical approaches to local needs and conditions.

In the study of Y.O. Adam *et al.* (2013) the discussion on the most effective forest management systems, specifically the systems for managing the non-timber resources, continues. Anthropogenic impact on the environment damages basic environmental functions, prompting a shift towards more sustainable management models. The sustainability of forest ecosystems is understood as the ability to maintain resources for a long time (Wezel *et al.*, 2020; Copena *et al.*, 2022).

C. Schulp *et al.* (2014) argue that, non-timber forest resources are currently a separate ecosystem service that is understudied due to what is often considered less important or because lack of data. Non-timber forest products provide numerous benefits to local communities, regional and national economies in many countries. However, they are rarely used in shaping forest policies and forest development strategies (Shackleton & Pandey, 2014). A. Gianotti & P. Hurley (2016) noted that there is a need for research on the non-timber resource base not only at the regional, but also at the local level, which will contribute to the best management of natural resources. This study was aimed at investigating the general trends and national characteristics of Ukraine regarding the harvesting of non-timber forest resources, coordinating terminology with international standards and identifying prospects for the development of this area in Ukraine.

Materials and Methods

Sources of information were processed by general scientific theoretical methods – analysis and synthesis. Using the method of analysis, the subject of this study – non-timber forest resources – was divided into components: secondary forest materials (harvesting of resin, bark, stumps, tree greens, tree sap), and secondary forest uses (hay harvesting, livestock grazing, apiary placement, wild fruit harvesting, mushrooms, medicinal plants, collection of forest litter, harvest of reeds). The synthesis method combined the components dissected during the analysis (secondary forest materials, secondary forest uses), establishing links between them, into a single whole – non-timber forest resources.

The factual material of the study included legislative and regulatory documents: Forest Code of Ukraine (Forest Code of Ukraine..., 1994), Laws of Ukraine: “On Plant Life” (Law of Ukraine No. 591-XIV..., 1999), “On Nature Reserve Fund of Ukraine” (Law of Ukraine No. 2456-XII..., 1992), “On Environmental Protection” (Law of Ukraine No. 1264-XII..., 1991), “On the Legal Regime of the Territory Exposed to Radioactive Contamination as a Result of the Chernobyl Disaster” (Law of Ukraine No. 791a-XII..., 1991), “Procedure for Special Use of Forest Resources” (Decree of the Cabinet of Ministers of Ukraine No. 761..., 2007), “Procedure for Harvesting Secondary Forest Materials and Implementation of Secondary Forest Uses in Forests of Ukraine” (Decree of the Cabinet of Ministers of Ukraine No. 449..., 1996), “Rules for Harvesting Resin in the Forests of Ukraine” (Decree of the Cabinet of Ministers of Ukraine No. 185..., 1996), “Rules for the Use of Beneficial Properties of Forests” (Order of the Ministry of Environmental No. 502..., 2012), “Regulations for the Special Use of Natural Plant Resources” (Order of the Ministry of Ecology and Natural Resources of Ukraine No. 61..., 2002). The list of legislative and regulatory documents covers the implementation of mechanisms for harvesting secondary forest materials and the implementation of secondary forest uses in the forests of Ukraine.

The study analysed the reporting materials of the State Agency for Forest Resources of Ukraine regarding the volume of harvesting of non-timber forest products for 2010-2020, as well as the distribution of income received according to types of non-timber forest products and in the context of regional departments of forestry and hunting for 2021.

Results

The legal framework for carrying out any activity in the forests of Ukraine is established by regulations (Tokarieva *et al.*, 2022). In the legislative and regulatory documents governing the harvesting of secondary forest materials, the implementation of secondary forest uses and the beneficial properties of forests, there is no explanation of the terms "non-tree" and "non-timber" forest resources. Therefore, there is a need for a clear understanding and distinction between these terms.

According to Forest Code of Ukraine No. 3852-XII (1994), forest resources are wood, technical, medicinal, and other forest products used to meet the needs of the population and production and reproduced in the forming of forest natural complexes.

For Ukraine, the practices of the European Union (EU) countries, which have formed a forestry sector with a full cycle of forest resources use, are important. The Food and Agriculture Organization (FAO) interprets non-timber forest products as raw materials, material and physical objects of biological origin, the source of which is forests, except for timber (Global Forest Resources Assessment, 2020). Thus, the English-language literature uses a term "Non-timber forest products". (Emery & Mclain, 2001; Kilchling, 2009). In German, there is an analogue of this term, "Nichtholzprodukte" – forest resources that are different from timber (Wolfslehner & Vacik, 2009).

Most languages adopted the term "non-timber forest products": Produkty niedrewniane (Polish), Ne medienos miško produktai (Lithuanian), Produse forestiere nelemnoase (Romanian), Nedřevěné lesní produkty (Czech), Produits forestiers non ligneux (French). Forest products obtained in the forestry production can be of wood origin, non-wood origin and animal (Fig. 1).

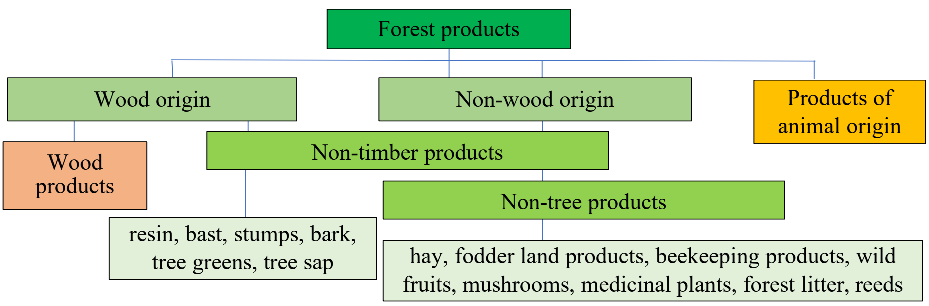

Figure 1. Classification of forest products

Source: developed by the authors based on the Forest Code of Ukraine No. 3852-XII (1994)

During 2015-2020, the forestry sector of Ukraine experienced a decrease in the volume of harvesting of non-timber forest resources (Tokareva *et al.*, 2022). In rural areas, the livelihood benefits of forests were more important to the local population than the value of the timber (Wahlén, 2017). Among the non-timber products in the forests of Ukraine, wild fruits, medicinal plants, mushrooms, tree sap, hay, and reeds were most often harvested (Fig. 2).

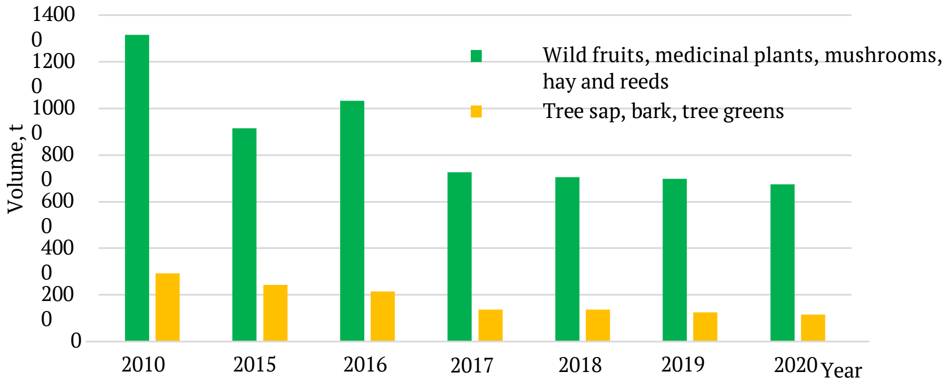

Figure 2. Harvesting of non-timber forest products in the forests of Ukraine

Source: developed by the authors, based on the Official website of the State Statistics Service of Ukraine (n.d.)

Currently, the main object of farming in the forests of Ukraine is harvesting the trunk part of a tree. Tree greens, bark, branches and stumps are conventional waste, for the liquidation of which considerable funds are spent, and secondary forest uses are carried out in small volumes. These are signs of poor management in forests. Therefore, it is relevant to use all wood and non-timber products of the forest.

According to V.P. Ryabchuk (1996) from 1 ha of a forest plot in Ukraine, on average, you can get: mushrooms – 65-70 kg; birch sap – 10 tons; honey – 100-200 kg; resin – 650 kg; wild fruits – 170-450 kg; coniferous extract – 5 kg; coniferous-vitamin flour – 6 tons; birch bark for tar – 6 tons; branch feed – up to 2 tons; herbal mass – 10-12 kg; other medicinal, technical, food raw materials – 30 kg.

The period of intensive harvesting of non-timber forest resources dates back to the 1960s–1980s, when in some regions of Ukraine, the comprehensive waste-free use of forests and their products yielded an average of 2.8 times more profit from 1 ha of forest than from realization of trunk part of the tree (Ryabchuk, 1996).

A classic example of the integrated use of forest resources in Ukraine was the management of forestry in the 1960-1980s by the Volyn Regional Department of Forestry and Hunting, where apart from timber, forestry enterprises harvested wild fruits, mushrooms, birch sap, medicinal plants, and honey resources, and the profit from non-timber forest products was several times higher than the profit from timber on the same forest plot. During the period, forestry enterprises harvested hundreds of tonnes of wild berries, mushrooms, birch sap, and even salted young shoots of common bracken and exported them to Japan. According to D.A. Telishevsky (1986), in the Volyn region in 1960, the production of the trunk part of the tree in the total volume of production was 94%, and in 1984 – 19.8%.

In Ukraine, the volume of harvesting of non-timber forest resources differs substantially (Fig. 3). This is explained by historical events (including the Chernobyl disaster), socio-cultural and national features.

Since Ukraine is one of the world's largest producers and exporters of honey, beekeeping at forestry enterprises is the most profitable. The geography of sales of Ukrainian honey covers over 50 countries in the world, including Germany, Poland, the USA, etc.

Harvesting of birch sap also has significant volumes, although it is carried out mainly in the

Volyn region. Until recently, 75% of birch sap was exported outside of Ukraine. Among the importing countries were Poland, Germany, Israel, Panama, USA, Czech Republic, Canada, Lithuania, Latvia, Estonia (Official website of the State Forest Resources Agency of Ukraine, n.d.).

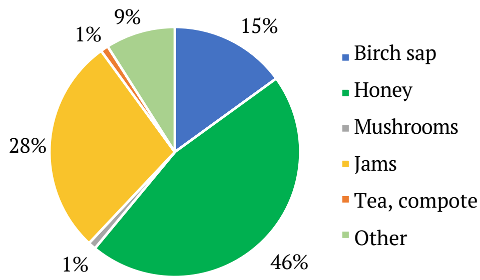

Figure 3. Distribution of income received by types of non-timber forest products for 2021

Source: developed by the authors based on reporting materials from the Official website of the State Forest Resources Agency of Ukraine (n.d.)

Berry species are recognized as the most important category of non-timber forest resources with the most profitable indicators in some countries (Romabai *et al.*, 2022). The most common berries in the forests of Ukraine are *Vaccinium myrtillus* L., *Rubus idaeus* L., *Rubus caesius* L., Oxycoccus palustris Pers., *Rhodococcum vitis-idaea* (L.) Avror., *Vaccinium uliginosum* L. Among wild berry plants, *Vaccinium myrtillus* L. is of the greatest industrial importance.

An increase the harvest of forest fruit and berry plants through plantation cultivation is possible. The promising species for plantation cultivation of berries in the conditions of Ukraine are as follows: *Aronia melanocarpa* (Michx.) Elliott, *Berberis vulgaris* L., *Juglans regia* L., *Vaccinium* oxycoccus (Hill) A. Gray, *Hippophae rhamnoides* L., *Rubus caesius* L., *Cornus mas* L., *Corylus avellana* (L.) H. Karst., *Vaccinium uliginosum* L., *Rubus idaeus* L., *Rosa canina* L.

Thus, *Vaccinium corymbosum* L. is successfully cultivated in the "Manevytsia forestry" branch of the SE "Lisy Ukrainy".

Each country has its own list of wild medicinal plants. Using a critical literature and inventory review, it is possible to identify the vast majority of medicinal plants (Soelberg *et al.*, 2015, Pohjanmies *et al.*, 2021). The most common forest medicinal plants of Ukraine are *Ledum palustre* L., *Vinca minor* L., *Menyanthes trifoliata* L., *Valeriana officinalis* L., *Persicaria hydropiper* (L.) Delarbre, *Rhamnus cathartica* L., *Convallaria majalis* L., *Pinus sylvestris* L., *Vaccinium myrtillus* L., *Juniperus communis* L., *Rubus idaeus* L., *Tilia cordata* Mill., *Viburnum opulus* L., *Melampyrum nemorosum* L., *Lycopódium clavátum* L., *Tanacetum vulgare* L., *Leonurus quinquelobatus* Gilib., *Fragaria vesca* L., *Helichrysum arenarium* L., *Betula pendula* Roth., *Vaccinium vitis-idaea* L., *Sambucus nigra* L., *Crataegus sanguinea* Pall., *Sorbus aucuparia* L., *Frangula alnus* Mill.

A promising area for generating additional income for forestry is the creation of tea plantations and medicinal plant plantations. In the Khmelnytskyi region, such an enterprise is the "Yarmolynets Forestry" branch of the State Enterprise "Forest of Ukraine".

Wild edible mushrooms are of socio-economic interest (Frutos, 2019). The mushroom resource trade is increasingly providing rural communities with additional income opportunities (Cai *et al.*, 2011). Industrial harvesting of mushrooms in Ukraine is limited to the following species: *Boletus edulis* Bull., *Suillus* spp., *Leccinum aurantiacum* (Bull.) Gray, *Leccinum scabrum* (Bull.) Gray, *Imleria badia* (Fr.) Wizzini, *Armillaria mellea* (Vahl) P. Kumm., *Cantharellus cibarius* Fr.

Territorial and regional features of the distribution of non-timber products differ substantially even within the same country. Habitat characteristics, namely soil fertility and plant density, are the most decisive factors in overall plant provision (Gianotti *et al.*, 2016).

Analysis of revenues received from the sale of non-timber products in 2021 in Ukraine shows that only four regional forestry and hunting departments (RFHD) are leaders: Volyn, Odesa, Poltava, and Khmelnytskyi RFHDs (Fig. 4).

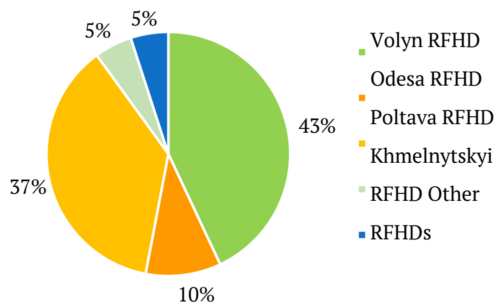

Figure 4. Distribution of income received from sales of non-timber products of RFHDs for 2021

Source: developed by the authors based on reporting materials from the Official website of the State Forest Resources Agency of Ukraine (n.d.)

Vinnytsia, Dnipropetrovsk, Zhytomyr, Zaporizhzhia, Ivano-Frankivsk, Kirovohrad, Luhansk, Mykolaiv, Sumy, Kharkiv, and Kherson RFHDs engaged in much smaller volumes of non-timber forest products harvesting.

Discussion

Studies of non-timber forest resources are usually devoted to certain types of products (mushrooms, berries, medicinal plants). M. Cai *et al.* (2011), P. Frutos *et al.* (2019), D. Copena *et al.* (2022) cover potentially possible reserves of individual resources. An analysis that covers all possibilities of integrated use of forests is covered by Y.O. Adam *et al.* (2013), T.S. Delgado *et al*. (2016), A.G.S. Gianotti & P.T. Hurley (2016).

Terminological clarifications of vocabulary about the harvesting of secondary forest materials and the implementation of secondary forest uses turned out to be relevant only for Ukraine, other countries apply the standardized, widely accepted term "non-timber forest products". An important stage in the development of science is the coordination of terminology not only within the country, but also at the international level. Based on the analysis of literary sources, the interpretation of words in Ukrainian and foreign languages, current legislative and regulatory documents, the authors of this study support classification of timber harvesting as timber resources of the forest, secondary forest materials and incidental forest uses as non-timber forest resources, and nontree forest resources as secondary forest uses.

The division of forest resources proposed by the authors for implementing in forestry practice requires coordination among scientists and practitioners and consolidation in legislative and regulatory documents. Notably, to clearly understand the terms and avoid their misinterpretation, the theory and practice of forestry requires the development of a separate state standard for non-timber forest resources, as well as detailed instructions on their harvesting and usage.

V.P. Ryabchuk (1996) showed that in multifunctional forest management, the main indicator is profit, regardless of its source, whether it was from timber harvesting, or from the sale of fruits, mushrooms, or from beneficial properties of the forest. Integrated forest management is one of the promising areas of development of forestry enterprises (Emery & Mclain, 2001). The latter can receive both direct economic effects as a result of economic diversification (focusing on the use of wood and other forest resources) and social effects that are important for the socio-economic development of local regions (Grammatikopoulou & Vačkářová, 2021; Helseth, 2022). A comparative analysis of the problematic issues of forestry activities in the countries of the world and Ukraine in studies (Kilchling *et al*., 2009; Delgado *et al*., 2016; Sisak *et al*., 2016) confirms the need for the development of industrial harvesting of non-timber forest resources. In particular the historical and cultural background of each country determines the priority and promising non-timber forest resources for specific conditions, and the economic component allows substantiating the advantages and disadvantages of economic activity in the area.

In EU countries in 2018, the volume of sales of non-timber forest resources included (Global Forest Resources Assessment, 2020): Christmas trees (28%), mushrooms (20%), fruits (18%), game meat (9%), wild plants (8%), honey (5%), resin (1%), bark (1%) and other products (10%). The comparison with the data obtained in Ukraine indicates that such products of non-timber resources as honey (46%), birch sap (15%) and jams (28%) have a larger share in the general list of non-timber resources of Ukraine compared to the data provided by FAO (Global Forest Resources Assessment, 2020). Unlike in EU the profit received from the sale of Christmas trees and hunting belongs to a separate category of forestry activities in Ukraine.

Although the distribution of wild non-timber forest plant species can vary substantially even within a country, there are certain trends and consumption needs (Cai *et al*., 2011; Pohjanmies *et al.*; 2021; Romabai *et al.*, 2022). Thus, among the wild berry plants, *Vaccinium myrtillus L.* is of industrial importance both in the world and in Ukraine. The most common berry species in the world grown in plantations is *Vaccinium corymbosum* L., and the industrial harvest of wild mushrooms in the European part of the continent is represented by *Boletus edulis* Bull., *Suillus* spp., *Cantharellus cibarius* Fr.

According to European countries, the material value of non-timber forest products corresponds to 1/6 of the value of timber, and the gathering of non-timber products by local residents for their personal needs (mainly mushrooms and berries) is on average 4 kg per person (Sisak *et al.*, 2016). From the conducted research, it is clear that the branches of the State Enterprise "Forest of Ukraine" harvest non-timber products in various volumes, and the facts of obtaining a substantially higher profit from the harvesting of non-timber products than from the sale of commercial timber took place in Ukraine in the middle of the last century. The importance of integrated use of non-timber forest products is important at the level of countries and even local communities both around the world (Gianotti & Hurley, 2016) and in Ukraine.

The studies of L. Osadchuk *et al.* (2016) and O.Tokarieva *et al.* (2022) proved that the gathering of wild non-timber forest products will improve the standard living of communities. Reserves of non-timber products of the forest substantially exceed the need for them. Therefore, considering the current economic situation at forestry enterprises, it is advisable to increase the volume of harvesting of secondary forest materials and the implementation of secondary forest uses.

According to G. Mujawamariya & A.A. Karimov (2014), products made from non-timber raw materials must usually compete with cheaper, less environmentally friendly analogues. Expanding the market for non-timber forest products requires organizational, innovation, and considerable marketing efforts and sales promotion. Thus, marketing is a vital component of the successful implementation of non-timber forest products.

Prospects for the development of harvesting non-timber forest products in Ukraine include improving the methods of their accounting, stock assessment, environmental monitoring and crop forecasting; working out ways to implement sustainable use of non-timber forest resources; economic assessment of non-timber forest resources as ecosystem services.

Conclusions

Establishing of the interpretation of the term "non-timber forest resources" in the theory and practice of forestry management, that covers resources of non-timber origin, was considered as necessary by the authors of this paper. Considering the division of forest resources into their types according to the Forest Code of Ukraine, non-tree forest resources should include incidental forest uses – hay harvesting, grazing, placing apiaries, harvesting wild fruits, mushrooms, medicinal plants, collecting forest floor and harvesting reeds. The term "non-timber forest resources" should be used in a broader sense as including types of forest resources besides timber harvesting, usage of secondary forest materials (resin, bast, stumps, bark, tree greens, tree sap) and incidental forest benefits. The above-mentioned terminology should be implemented in current legislative and regulatory documents. A state standard should be developed to clearly cover the interpretation of terms related to non-timber forest products, including instructions for harvesting them. The use of the terms "non-wood forest resources" and "non-tree forest resources" in the proposed interpretation will contribute to their clear understanding and help avoid ambiguities.

The possibility of harvesting secondary forest materials, implementing incidental forest purposes and using the benefical properties of forests contributes to comprehensive farming in the forests of Ukraine. The use of forest resources of wood and non-timber origin increases the complex productivity of forests, increases the economic effect of each hectare of forest plot, meets the industry's demand for raw materials, and also contributes to increasing revenues to local budgets and generating employment.

Reserves of non-timber products of the forest substantially exceed the need for them. Therefore, considering the current economic situation at forestry enterprises, it is advisable to increase the volume of harvesting of secondary forest materials and the implementation of secondary forest uses.

Among the promising areas of scientific research of non-timber products of Ukrainian forests are the improvement of methods of its accounting, inventory assessment, environmental monitoring, and crop forecasting.

Conflict of Interest

The authors declare no conflict of interest.

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References

[1] Adam, Y.O., Pretzsch, J., & Pettenella, D. (2013). Contribution of non-timber forest products livelihood strategies to rural development in drylands of Sudan: Potentials and failures. *Agricultural Systems*, 117, 90-97. doi: 10.1016/j.agsy.2012.12.008.

[2] Cai, M., Pettenella, D., & Vidale, E. (2011). Income generation from wild mushrooms in marginal rural areas. *Forest Policy and Economics*, 13(3), 221-226. doi: 10.1016/j.forpol.2010.10.001.

[3] Copena, D., Pérez-Neira, D., Vázquez, A.M., & Simón, X. (2022). Community forest and mushrooms: Collective action initiatives in rural areas of Galicia. *Forest Policy and Economics*, 135, article number 102660. doi: 10.1016/j.forpol.2021.102660.

[4] Decree of the Cabinet of Ministers of Ukraine No. 185 "On Approval of the Rules for Harvesting Resin in the Forests of Ukraine". (1996, February). Retrieved from https://zakon.rada.gov.ua/laws/show/185-96-%D0%BF#Text.

[5] Decree of the Cabinet of Ministers of Ukraine No. 449 "On Approval of the Procedure for the Procurement of Secondary Forest Materials and the Implementation of Secondary Forest uses in the Forests of Ukraine". (1996, April). Retrieved from https://zakon.rada.gov.ua/laws/show/449-96-%D0%BF#Text.

[6] Decree of the Cabinet of Ministers of Ukraine No. 761 "On the Settlement of Issues Regarding the Special Use of Forest Resources". (2007, May). Retrieved from https://zakon.rada.gov.ua/laws/show/761-2007-%D0%BF#Text.

[7] Delgado, T.S., McCall, M.K., & López-Binqüist, C. (2016). Recognized but not supported: Assessing the incorporation of non-timber forest products into Mexican forest policy. *Forest Policy and Economics*, 71, 36-42. doi: 10.1016/j.forpol.2016.07.002.

[8] Emery, M., & Mclain, R. (2001). *Non-timber forest products. Medicinal herbs, fungi, edible fruits and nuts, and other natural products from the forest*. Boca Raton: CRC Press.

[9] Forest Code of Ukraine No. 3852-XII. (1994, January). Retrieved from https://zakon.rada.gov.ua/laws/show/3852-12#Text.

[10] Frutos, P., Rodríguez-Prado, B., Latorre, J., & Martínez-Peña, F. (2019). Environmental valuation and management of wild edible mushroom picking in Spain. *Forest Policy and Economics*, 100, 177-187. doi: 10.1016/j.forpol.2018.12.008.

[11] Gianotti, A.G.S., & Hurley, P.T. (2016). Gathering plants and fungi along the urban-rural gradient: Uncovering differences in the attitudes and practices among urban, suburban, and rural landowners. *Land Use Policy*, 57(30), 555-563. doi: 10.1016/j.landusepol.2016.06.019.

[12] Global Forest Resources Assessment. (2020). Retrieved from https://reliefweb.int/report/world/global-forest-resources-assessment-2020-key-findings?gclid=Cj0KCQjwuLShBhC_ARIsAFod4fJs1mzd5go5ODhcMLOy2aLLvgFwc_CJ4E__bal_HPwk5eHBH5by1_gaAg4uEALw_wcB.

[13] Grammatikopoulou, I., & Vačkářová, D. (2021). The value of forest ecosystem services: A meta-analysis at the European scale and application to national ecosystem accounting. *Ecosystem Services*, 48, article number 101262. doi: 10.1016/j.ecoser.2021.101262.

[14] Helseth, E.V., Vedeld, P., Framstad, E., & Gómez-Baggethun, E. (2022). Forest ecosystem services in Norway: Trends, condition, and drivers of change (1950-2020). *Ecosystem Services*, 58, article number 101491. doi: 10.1016/j.ecoser.2022.101491.

[15] Hoogstra-Klein, M.A., Brukas, V., & Wallin, I. (2017). Multiple-use forestry as a boundary object: From a shared ideal to multiple realities. *Land Use Policy*, 69, 247-258. doi: 10.1016/j.landusepol.2017.08.029.

[16] Kilchling, P., Hansmann, R., & Seeland, K. (2009). Demand for non-timber forest products: Surveys of urban consumers and sellers in Switzerland. *Forest Policy and Economics*, 11(4), 294-300. doi: 10.1016/j.forpol.2009.05.003.

[17] Law of Ukraine No. 1264-XII "On Environmental Protection". (1991, June). Retrieved from https://zakon.rada.gov.ua/laws/show/1264-12#Text.

[18] Law of Ukraine No. 2456-XII "On Nature Reserve Fund of Ukraine". (1992, June). Retrieved from https://zakon.rada.gov.ua/laws/show/2456-12#Text.

[19] Law of Ukraine No. 591-XIV "On Flore". (1999, April). Retrieved from https://zakon.rada.gov.ua/laws/show/591-14#Text.

[20] Law of Ukraine No. 791a-XII "On the Legal Regime of the Territory Exposed to Radioactive Contamination as a Result of the Chernobyl Disaster". (1991, February). Retrieved from https://zakon.rada.gov.ua/laws/show/791%D0%B0-12#Text.

[21] Mujawamariya, G., & Karimov, A.A. (2014). Importance of socio-economic factors in the collection of NTFPs: The case of gum arabic in Kenya. *Forest Policy and Economics*, 42, 24-29. doi: 10.1016/j.forpol.2014.02.005.

[22] Myhal, A.V, & Bokoch, V.V. (2017). *Non-timber resources*. Uzhhorod: Hoverla.

[23] Official website of the State Forest Resources Agency of Ukraine. (n.d.). Retrieved from https://forest.gov.ua/en.

[24] Official website of the State Statistics Service of Ukraine. (n.d.). Retrieved from http://www.ukrstat.gov.ua.

[25] Order of the Ministry of Ecology and Natural Resources of Ukraine No. 61 "On the Approval of the Instruction on the Procedure for Establishing Standards for the Special Use of Natural Plant Resources". (2002, February). Retrieved from https://zakon.rada.gov.ua/laws/show/z0202-02#Text.

[26] Order of the Ministry of Environmental No. 502 "On Approval of the Rules for the Use of Beneficial Properties of Forests". (2012, August). Retrieved from https://zakon.rada.gov.ua/laws/show/z1536-12#Text.

[27] Osadchuk, L., Ryabchuk, V., & Grechanyk, R. (2016). The role of non-timber forest resources for sustainable forestry management in Ukraine. *Scientific Works of the Forestry Academy of Sciences of Ukraine*, 14, 92-97.

[28] Pohjanmies, T., Jašková, A., Hotanen, J.-P., Manninen, O., Salemaa, M., Tolvanen, A., & Merilä, P. (2021). Abundance and diversity of edible wild plants in managed boreal forests. *Forest Ecology and Management*, 491, article number 119151. doi: 10.1016/j.foreco.2021.119151.

[29] Romabai, W., Pamei, T., Pf, M., Nevidita, L., & Panmei, R. (2022). Assessment of economically important tree-based NTFPs in Indo-Burma region, Manipur, India. *Forests, Trees and Livelihoods*, 32(1), 1-11. doi: 10.1080/14728028.2022.2146606.

[30] Ryabchuk, V.P. (1996). *Non-tree products of the forest: Understudy*. Lviv: World.

[31] Schulp, C.J.E., Thuiller, W., & Verburg, P.H. (2014). Wild food in Europe: A synthesis of knowledge and data of terrestrial wild food as an ecosystem service. *Ecological Economics*, 105, 292-305. doi: 10.1016/j.ecolecon.2014.06.018.

[32] Shackleton, C.M., & de Vos, A. (2022). How many people globally actually use non-timber forest products? *Forest Policy and Economics*, 135, article number 102659. doi: 10.1016/j.forpol.2021.102659.

[33] Shackleton, C.M., & Pandey, A.K. (2014). Positioning non-timber forest products on the development agenda. *Forest Policy and Economics*, 38, 1-7. doi: 10.1016/j.forpol.2013.07.004.

[34] Sisak, L., Riedl, M., & Dudik, R. (2016). Non-market non-timber forest products in the Czech Republic – Their socio-economic effects and trends in forest land use. *Land Use Policy,* 50, 390-398. doi: 10.1016/j.landusepol.2015.10.006.

[35] Soelberg, J., Asas, A., Akwetey, G., & Jäger, A.K. (2015). Historical versus contemporary medicinal plant uses in Ghana. *Journal of Ethnopharmacology*, 160, 109-132. doi: 10.1016/j.jep.2014.11.036.

[36] Telishevsky, D.A. (1986). *Complex use of non-tree forest production*. moscow: Forest industry.

[37] Tokareva, O., Sobko, T., & Tovarnytskyi, V. (2018). Prospects for harvesting non-timber forest products in Chernivtsi region. *Forestry and Landscape-Park Management,* 14, 1-9.

[38] Tokarieva, O.V., Levchenko, V.V., & Lakyda, M.O. (2022). *Non-timber forest resources*. Kyiv: KOMPRINT.

[39] Wahlén, C.B. (2017). Opportunities for making the invisible visible: Towards an improved understanding of the economic contributions of NTFPs. *Forest Policy and Economics*, 84, 11-19. doi: 10.1016/j.forpol.2017.04.006.

[40] Wezel, A., Gemmill, B., Bezner, R., Barrios, E., Rodrigues, A., & Sinclair, F. (2020). Agroecological principles and elements and their implications for transitioning to sustainable food systems. A review. *Agronomy for Sustainable Development*, 40. doi: 10.1007/s13593-020-00646-z.

[41] Wolfslehner, B., & Vacik, H. (2009). *Forstliche Nichtholzprodukte und Dienstleistungen in Österreich*. Wien: Institut für Waldbau.

Термінологічні засади та перспективи використання недеревинної продукції лісів України

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Анотація. Ведення господарства у лісах України повинно здійснюватися на принципах безперервного та раціонального лісокористування шляхом комплексного застосування лісових ресурсів. Разом із тим існує потреба у розрізненні та правильному розумінні термінів, які використовуються у теорії та практиці ведення лісового господарства. Тому з метою узгодження термінології проведено аналіз відповідних нормативних актів, а також української та зарубіжної літератури. Для роботи з джерелами інформації були використані загальнонаукові теоретичні методи – аналіз та синтез. Обґрунтовано вживання та розуміння термінології, яка пов'язана з використанням лісових ресурсів. Узагальнено визначення і тлумачення термінів «побічні користування лісом», «недеревні ресурси лісу», «недеревинні ресурси лісу» у діючих законодавчо-нормативних актах, тлумачному словнику української мови, державному стандарті України, українській енциклопедії лісівництва, українській та іноземній лісівницькій літературі. Запропоновано поділ лісових ресурсів на деревні, недеревні та недеревинні з подальшим узгодженням такої класифікації серед науковців та практиків лісового господарства. Встановлено найбільші обсяги заготівлі серед другорядних лісових матеріалів та побічних лісових користувань за 2010–2020 рр. Проаналізовано розподіл отриманого доходу за видами недеревинної продукції лісу та у розрізі обласних управлінь лісового і мисливського господарства за 2021 рік. Наведені поширені в Україні види дикорослих плодових та лікарських рослин, грибів. Запропоновані перспективні види для плантаційного вирощування. Узагальнені напрямки отримання додаткового доходу від реалізації недеревинної продукції лісів. Представлено аналіз та перспективи використання недеревинної лісової продукції, що може слугувати теоретичною та практичною основою для комплексного ведення господарства у лісах України. Отримані результати можуть бути використані при заготівлі недеревинної продукції лісів з урахуванням регіональних особливостей країни

Ключові слова: дикорослі плоди; лікарські рослини; гриби; березовий сік; законодавчо-нормативні документи

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