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Infestation of ash emerald ash borer *Agrilus planipennis* Fairmaire, (*Coleoptera: Buprestidae*) on the territory of National University of Life and Environmental Sciences (NULES) of Ukraine

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Abstract. The aim of the study was to assess the sanitary condition of ash trees of the genus *Fraxinus* spp. on the territory of NULES of Ukraine and to monitor the number of invasive species *Agrilus planipennis*. The inventory data of 2021-2023 were presented, where it was noted that the condition of 66% of ash trees was characterised as good. A detailed survey in 2024 revealed a rapid deterioration of ash trees throughout the study area. It was found that a significant weakening of *Fraxinus* spp. trees was noted on the territory of the Botanical Garden of the National University of Life Sciences of Ukraine and near the stadium. It was worth noting that 13% of trees without signs of damage were located in the depths of the forest, as the emerald ash borer was a potential feeder for trees growing openly, although with a significant distribution the insect can inhabit trees in the depths of the plantation. During the detailed forest pathology survey, *Agrilus planipennis* adults and D-shaped flight holes were found. The number of typical D-shaped flight holes per 1 dm^2 was calculated to determine the density of settlement and production of young beetles. The maximum number of exit holes per 1 dm^2 was 4.2 ± 1.8, so with an average number of exit holes of 1-2.4 per 1 dm^2, 35 to 100% of the trees inhabited by the moth could dry out within 2-3 seasons. To determine the number and distribution of *Agrilus planipennis* adults, pheromone traps' surveys with artificially synthesised pheromone and traps without pheromone to attract insects by colour were conducted. According to the results of the counts, it was found that adults of *Agrilus planipennis* were presented only in traps with artificially synthesised pheromones

Keywords: *Fraxinus* spp.; monitoring; *Agrilus planipennis*; pheromone traps; invasive species

Introduction

Forests were increasingly being affected by a variety of impacts from biological invasions, including the spread of invasive species that spread naturally or by humans. Urban forests are more adversely affected because they are strongly affected by anthropogenic influence (Sovakov *et al.*, 2020). Invasive species had a possibility to expand and represent a potential threat to the flora and fauna of natural ecosystems, such species created competition in ecological niches, and if widespread, could cause the extinction of native species, displacing them and reducing ecosystem biodiversity. Given their high ecological potential, such species had a wide ecological amplitude, stress tolerance, intensive population growth, and a high degree of naturalisation. Aggressive species used the resources of the new environment that were not available to native species and significantly affect the ecosystem's homeostasis, transforming it.

According to A.M. Liebhold *et al.* (2017), under intense impacts, the consequences of invasion included changes in the composition of tree species, changes in forest succession, reduced biodiversity, and altered nutrient, carbon, and water cycles resulting from competition with native species, as well as trophic impacts that can lead to major changes in the structure of the biocenosis. R. Vasylyshyn *et al.* (2023) researched those irreversible changes in the natural environment due to increased synanthropisation, in particular of the adventive flora and fauna, had a destructive impact on the development of vegetation cover and negatively affected the ability of forest ecosystems to effectively ensure the bioproduction process.

Trees of the ash genus *Fraxinus* spp. had significant ecological and economic potential, were typical mesotrophs and occurred as subdominants in forest ecosystems. The researchers showed that due to climate change, there was a problem of ash tree drying out, the main causes of which were climatic factors, chalar necrosis caused by the invasive pathogen *Hymenoscyphus fraxineus* L. and the ash borer *Agrilus planipennis Fairmaire* L. (emerald ash borer (EAB), which in the future may leaded to the complete disappearance of ash trees from forest ecosystems (Drogvalenko *et al.,* 2019; Meshkova *et al.*, 2024). Natural ash-dominated forests were concentrated mainly on rich loamy and clayey soils in river floodplains and were characterised by a diverse species composition of trees, shrubs, and grasses. I. Matsiakh & V. Kramarets (2014) noted that derivative ash plantations most often grow on forest loamy soils and podzolized chernozems in the zone of oak and mixed forests, mostly single-aged, simplified structure, usually artificially created on the site of cut down complex oak forests. On the territory of Ukraine, stands of ash covered an area of 390,4 thousand hectares and were most often founded in the Forest-Steppe (57.7%), mainly in its right-bank part (38.4%), a significant part grew in the Steppe zone (32.0%), mainly in its north, as well as in Polissya – 4.8%, mountainous Crimea – 2.8% and the Carpathian zone – 2.7% (Bala, 2016). The authors S. Koval *et al.* (2023) claimed that in such plantations, along with ash, common oak (*Quercus robur* L.), common hornbeam (*Carpinus betulus* L.), forest beech (*Fagus sylvatica* L.), heart-leaved linden (*Tillia cordata* Mill.), and sharp-leaved maple (*Acer platonoides* L.) could grow. Black elderberry (*Sambucus nigra* L.) and blood-red sweed (*Swida sanguinea* L.) were found in the undergrowth.

Significant fluctuations in the drying area from year to year could be attributed to a variety of factors, thus, the reasons for the deterioration of the sanitary condition of ash plantations were climate change and anthropogenic pressure, which caused outbreaks of mass reproduction of insects and epiphytosis of pathogens. Thus, the assessment of the sanitary condition of plantations, early diagnosis of pathogens and the dynamics of insect numbers were relevant in a comprehensive study of ash tree drying factors. The priority was to identify the causes of ash drying in the study area and find effective measures to slow down this process in order to avoid disrupting the stable functioning of forest ecosystems. This was especially true in urbanised areas, where the ecosystem functions of green spaces were an important component of creating a comfortable living environment (Vasylyshyn *et al.*, 2023).

The aim of the study was to investigate the main factors of the rapid deterioration of the sanitary condition of trees of the ash genus *Fraxinus* spp. due to the invasion of *Agrilus planipennis* using pheromone monitoring.

Materials and Methods

The object of the study was the main factors of rapid drying of trees of the ash genus *Fraxinus* spp. under the intensive influence of natural factors. The subject of the study was the monitoring of the spread of the invasive species *Agrilus planipennis* on the trees of the ash genus *Fraxinus* spp. on the territory of the National University of Life and Environmental Sciences (NULES) of Ukraine, Kyiv.

The surveys were based on the materials of the inventory of green spaces on the territory of NULES of Ukraine, which were conducted in 2021-2023 by the Department of Forest Mensuration and Forest Management. The inventory of trees was carried out in accordance with the regulations, namely the "Instruction on Inventory of Green Areas in Settlements of Ukraine", approved by the Order of the State Committee for Construction, Architecture and Housing Policy of Ukraine No. 226 of 24.12.2001 (Order of State Committee..., 2001).

During the inventory, the category of the tree's qualitative condition was established:

good, satisfactory, unsatisfactory. According to the guidelines, healthy trees were in a good condition, normally developed, with dense foliage, evenly distributed on the branches, leaves of normal size and colour, no signs of diseases and pests, wounds, damage to the trunk and skeletal branches, or hollows. Satisfactory condition – trees were healthy, but with signs of slow growth, with an unevenly developed crown, few leaves on the branches, minor mechanical damage and small hollows. Unsatisfactory condition – trees were very weakened, trunks were curved, crowns were poorly developed, there were dry and drying branches, the growth of annual shoots was insignificant, trunks were mechanically damaged, hollows (Order of State Committee..., 2001). The mapping of the trees and the general area was carried out using Quantum GIS 3.22 software (Fig. 1).

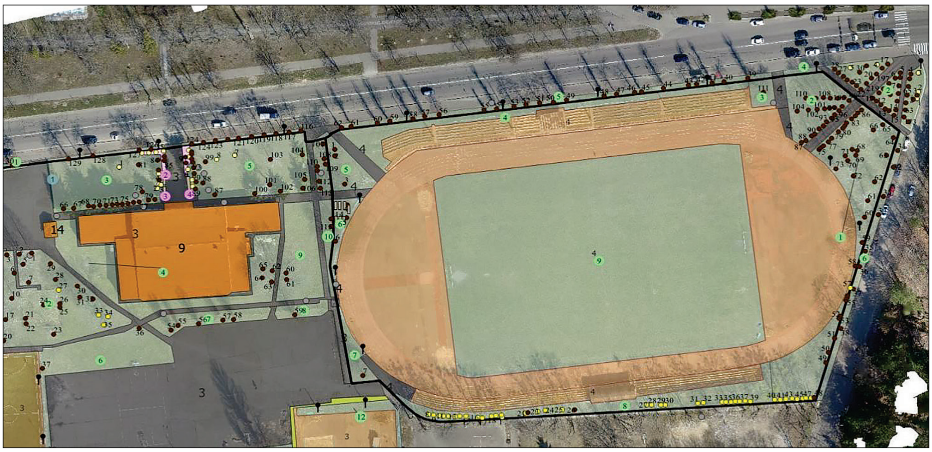

Figure 1. Fragment of the mapping of trees and the general area
Note: trees of the ash genus *Fraxinus* spp. were marked in yellow on the map
Source: developed by the authors

Detailed forest pathological surveys in the centres of drying out of ash trees of the genus Fraxinus spp. were carried out in accordance with generally accepted methods (Goychuk *et al.*, 2012; Methodological guidelines..., 2020; Puzrina *et al.*, 2022). To determine the number and distribution of *Agrilus planipennis* adults, pheromone traps (glue and barrier) with artificially synthesised *Agrilus planipennis* pheromone (produced by BioChemTech, Ukraine) and traps without pheromone with green and purple insect attraction were used (Matsiakh, 2019; International Plant Sentinel Network, 2023) (Fig. 2). Pheromone traps were hung at a height of 3.0 to 4.0 m above the ground on the first living branch of ash. Barrier and glue traps were used to capture *Agrilus planipennis* adults, for this purpose they were attached to the trunk of living trees between living and dead shoots. When hanging the traps, weather conditions and the duration of the flight of adults of the ash emerald ash borer *Agrilus planipennis* were taken into account (Puzrina *et al.*, 2022; Levchenko *et al.*, 2023). The number of adults was monitored after 14 days.

The collection of experimental material was carried out in the following sequence: transfer of insects from the collector to the container and identification of insects in Petri dishes (Fig. 3).

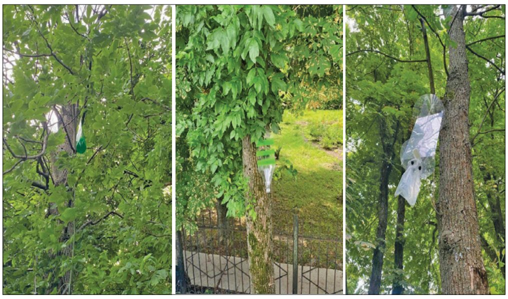

Figure 2. General view of tree traps
Source: photo by the authors

Figure 3. Collecting insect from traps
Source: photo by the authors

Number of insect populations that inhabited trees in the drying centres, namely the number, prevalence, production of young beetles (number of flight holes) and settlement density, were counted by the pallet method on model trees of common ash (Methodological guidelines..., 2020; Puzrina *et al.*, 2022). Within the identified settlement areas, counting pallets to determine the density of settlement and the production of young beetles by the number of typical D-shaped flight holes per 1 dm^2 were used. The average number of exit holes was calculated by counting on three sides of each tree from the location. The average population size of *Agrilus planipennis* was calculated based on the results obtained at the specified location. Experimental studies of plants complied with national and international recommendations. The authors followed the standards of the Convention on Biological Diversity (1992). In the office, the work was limited to processing the collected materials and analysing the results of the research.

Results and Discussion

During the inventory and mapping work in 2023 (Bilous *et al.*, 2024), it was found that there were 167 ash trees on the territory of NULES of Ukraine. Their main localisation was found in the Botanical Garden (89 trees) and in the area near the stadium (44 trees) (Fig. 4).

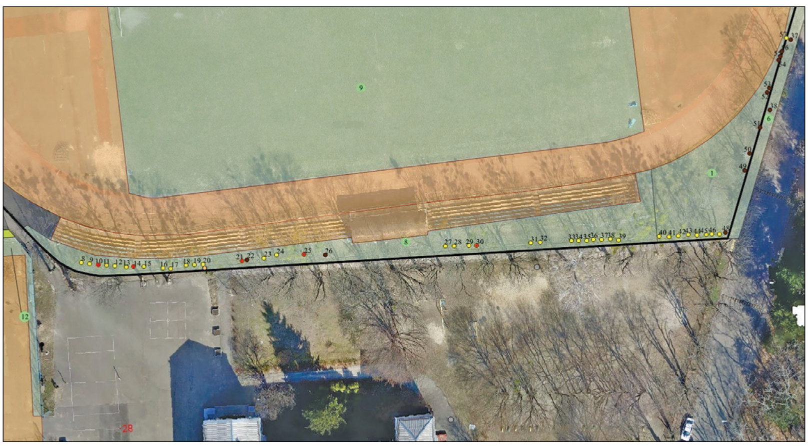

Figure 4. Fragment of mapping of common ash trees near the stadium of NULES of Ukraine
Note: trees of the ash genus *Fraxinus* spp. were marked in yellow on the map
Source: developed by the authors

The mapping data shows that the ash trees were in a regular planting along the stadium stands. During the inventory of 2023, the general condition of ash trees was determined based on the results of a reconnaissance survey (Fig. 5).

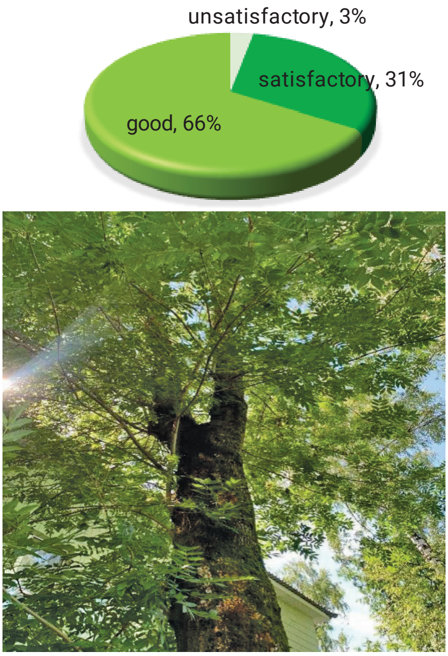

Figure 5. General condition of ash trees of the genus *Fraxinus* spp. (as of 2023) on the territory of NULES
Source: developed by the authors

It should be noted that according to the inventory in 2023, trees of the ash genus *Fraxinus* spp. were dominated by trees in good and satisfactory condition, and no visual signs of tree weakening during the inventory were noted. During the current reconnaissance survey in June 2024, pathological signs of ash trees drying out, namely crown defoliation and the presence of dry tops, were detected (Fig. 6).

A detailed survey revealed a rapid deterioration of ash trees throughout the study area. The results of the survey indicated a deterioration in the sanitary condition (Table 1).

Figure 6. Crown defoliation and ash tree dryness
Source: photo by the authors

Table 1. Results of surveys of *Agrilus planipennis* ash damage

Tree location (address)	Number of trees, amount				
	total	including			
		no signs of damage	signs of initial damage	moderately damaged	severely damaged
7, Horikhuvatskyi Shlyakh Str.	2	1	1	–	–
7a, Horikhuvatskyi Shlyakh Str.	1	–	1	–	–
3, Horikhuvatskyi Shlyakh Str.	1	1	–	–	–
11, Horikhuvatskyi Shlyakh Str.	9	2	6	1	–
8, Blakytnoho Str.	2	–	2	–	–

Table 1, Continued

Tree location (address)	Number of trees, amount				
	total	including			
		no signs of damage	signs of initial damage	moderately damaged	severely damaged
4, Orikhuvatska Str.	7	2	4	1	–
12B, Heroiv Oborony Str.	1	1	–	–	–
12, Heroiv Oborony Str.	4	1	2	1	–
4, Selykhozemichnyi Ln.	3	–	2	1	–
14, Heroiv Oborony Str.	1	1	–	–	–
18A, Heroiv Oborony Str. (stadium)	44	–	4	28	12
16, Polkovnyka Potekhina Str.	3	–	2	1	–
2A, Heroyiv Oborony Str. (Botanical garden)	89	12	21	33	23
Total	**167**	21	45	66	35

Note: signs of initial damage – dry tops, presence of adults; moderately affected – openwork, drying out of individual shoots, presence of bark cracking; severely affected – defoliation, crown 50%, drying out of parts of the tree, bark peeling
Source: developed by the authors

It was found that a significant weakening of ash trees of the *Fraxinus* spp. genus was noted on the territory of the Botanical Garden of the NULES of Ukraine (21 trees with signs of initial damage, 33 and 23 ash trees moderately and severely damaged, respectively, and 12 trees without signs of damage) and near the stadium (4 trees with signs of initial damage, 28 and 12 common ash trees moderately and severely damaged, respectively) (Fig. 7). 13% of trees without signs of damage were located in the depths of the forest, and as for the emerald ash borer, potential hosts were trees growing openly, although with a significant distribution the insect was able to inhabit trees in the depths of the forest were noted (Meshkova *et al.*, 2024).

For successful and effective control of the ash emerald ash borer, its early detection was very important. The first emergence of *Agrilus planipennis* beetles coincided with the flowering period of *Robinia pseudoacacia* L., which occured in May-June in Ukraine, so this phenological indicator could serve as an indicator of the appearance of ash borer adults in different regions (Herms & McCullough, 2019).

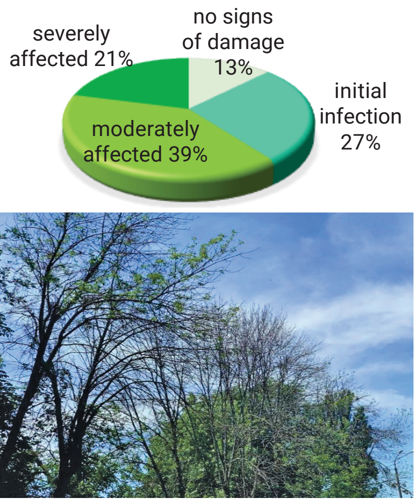

Figure 7. General condition of trees of the ash genus *Fraxinus* spp. (as of 2024)
Source: developed by the authors

Adults fed on ash leaves, after reaching sexual maturity, they mated in the crowns of trees, and females laid eggs on the surface or in cracks in the bark. The peak of egg laying and larval emergence usually occurred between early June and mid-August, depending on the region and weather conditions. The egg stage usually lasted from 7 to 18 days, which also depended on temperature. The newly hatched larvae make their way through the bark to the cambium, consuming phloem and outer xylem, forming powder-filled passages (Matsiakh, 2019).

In the first year of settlement, it was difficult to diagnose the presence of *Agrilus planipennis*. The first signs of infestation could be bird pecking of the bark and the presence of larval burrows under the bark. The characteristic D-shaped holes on trunks and branches appeared in the next year after the infestation of trees by the bark beetle. Infested trees usually had a thinned crown, dechromed leaves, swelling, cracks and necrosis on branches and thin trunks. Secondary shoots developed along the trunk and in the basal part of the trunks. In the third year of settlement, the crown was significantly thinned out, with many branches dying off and numerous D-shaped flight holes on the trunk and branches.

A clear sign of *Agrilus planipennis* infestation was the presence of D-shaped holes for adults to exit, which were difficult to detect but a reliable sign that the population was growing. As the insect's population grows, its natural enemy was the woodpecker (Schans *et al.*, 2020).

During a detailed forest pathology survey, adults of *Agrilus planipennis* and characteristic D-shaped flight holes were found (Fig. 8).

The number of typical D-shaped exit holes per 1 dm^2 was used to determine the settlement density and production of young beetles (Table 2).

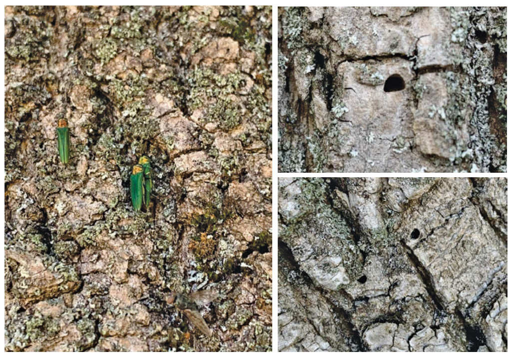

Figure 8. Adults and flight holes of the ash emerald ash moth *Agrilus planipennis*
Source: photo by the authors

Table 2. Degrees of settlement of *Agrilus planipennis* trees

Location of trees (address)	Number of trees, amount	Production of stem pests (average number of exit holes and average error per 1 dm^{-2})
7, Horikhuvatskyi Shlyakh Str.	2	2.2 ± 0.2
7a, Horikhuvatskyi Shlyakh Str.	1	2.7 ± 1.3
3, Horikhuvatskyi Shlyakh Str.	1	0
11, Horikhuvatskyi Shlyakh Str.	9	0.9 ± 0.2
8, Blakytnoho Str.	2	0
4, Orikhuvatska Str.	7	2.6 ± 0.6
12B, Heroiv Oborony Str.	1	0
12, Heroiv Oborony Str.	4	0
4, Selykhozemichnyi Ln.	3	1.3 ± 0.2
14, Heroiv Oborony Str.	1	0
18A, Heroiv Oborony str. (stadium)	44	4.2 ± 1.8
16, Polkovnyka Potekhina Str.	3	1.1 ± 0.3
2A, Heroyiv Oborony str. (Botanical Garden)	89	3.8 ± 1.1
Total	**167**	-

Source: developed by the authors

The number of typical D-shaped exit holes per 1 dm^2 was used to determine the settlement density and production of young beetles (Table 2). According to D. Crook *et al.* (2012) and I. Matsiakh (2019), males and females were sensitive to ultraviolet light, violet and green ranges of the electromagnetic spectrum, and fertilised females were also sensitive to light in the red, with beetles attracted to green or violet traps set both in open spaces and under the canopy of the plantation. The trees on which pheromone traps were hung were marked on the map (Fig. 9).

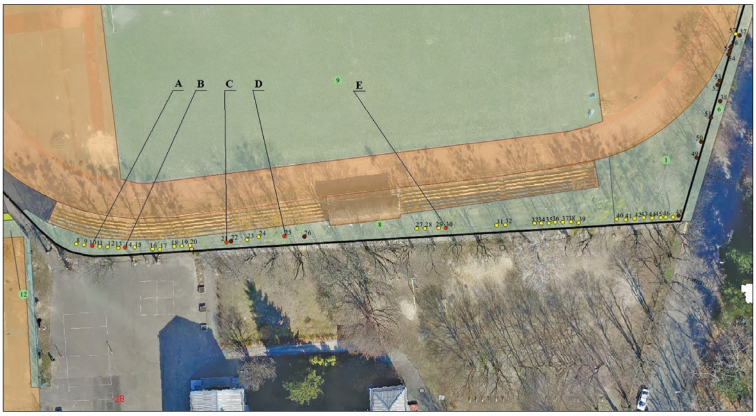

Figure 9. Location of the traps
Note: A – glue trap with pheromone; B – barrier transparent trap with purple stripes without pheromone; C – barrier transparent trap without pheromone; D – barrier transparent trap with green stripes without pheromone; E – barrier transparent trap with pheromone
Source: developed by the authors

During the inspection of the traps, the effectiveness of their use was assessed, but some traps were blocked by leaves, which was associated with a decrease in daylight hours and a slowdown in photosynthesis, which caused the physiological process of leaf fall.

According to A. Morozko *et al.* (2021), different trophic groups of insects damaged plant parts, caused damage to the assimilation apparatus, young shoots, generative organs, and trunk, respectively, but the spread of phytophages and their impact on plants depends on the insect species, population density, and plant response to damage, which has been confirmed by our research. According to the results of species diversity determination, it could be noted that the traps were mainly used for capturing insects of the *Coleoptera* order. In the barrier transparent trap with purple stripes without pheromone, representatives of the families *Curculionidae* and *Chrysomelidae* were found, in the barrier transparent trap without pheromone, insects of the subfamily *Scolytinae* of the family *Curculionidae* dominated. Representatives of the order *Hymenoptera* were found only in the barrier transparent trap with green stripes without pheromone. The family *Buprestidae* was represented by *Agrilus planipennis*, but adults were presented only in traps with artificially synthesised pheromones, so it could be noted the low efficiency of green and purple traps. It should be noted that all detected insects except *Agrilus planipennis* were not potential pests of ash trees of the genus *Fraxinus* spp.

The issue of *Agrilus planipennis* spread was quite relevant, as the invasive species had no natural enemies in our environment, which made it difficult to control. The issue of penetration and biology of invasive organisms was being studied by specialists of a separate working group of IUFRO, Invasive Species Specialist Group – ISSG, World Conservation Union – IUCN, European Plant Protection Organisation – EPPO, and a system of inventory of invasive species for Europe – Delivering Alien Invasive Inventories for Europe – DAISIE – has been created (Roques *et al.*, 2010).

The emerald ash borer (*Agrilus planipennis*, EAB) had been a focus of global entomological and forestry research due to its devastating impact on ash tree species (*Fraxinus* spp.) worldwide. Its rapid expansion and destructive behaviour have been extensively studied across various ecological, geographical, and management contexts.

The spread of the invasive species *Agrilus planipennis Fairmaire*. (*Coleoptera: Buprestidae*) caused intensive mortality of ash trees of the genus *Fraxinus* spp. in plantations throughout Europe (Flo *et al.*, 2015) and North America (Sun *et al.*, 2024). *Agrilus planipennis* originates from China and Korea, where it primarily attacks trees under stress, where the coevolutionary resistance mechanisms against this pest are weakened. According to V. Meshkova *et al.* (2024), the ash emerald ash borer was first discovered in the eastern part of Ukraine (Luhansk region) in 2019 and was spreading in all plantations with ash trees very fast. The ongoing infestation of *Agrilus planipennis* in Ukraine mirrors global trends while presenting unique challenges due to the region's specific ecological and climatic conditions. Studies such as those by T.V. Kucheryavenko *et al.* (2019) and V. Meshkova *et al.* (2024) provided critical insights into local dynamics, which are essential for developing tailored management strategies. The rapid spread of the pest in Kyiv in a short time indicated an increased threat of further spread to the West (Meshkova *et al.*, 2024). The role of host plants in shaping EAB distribution had been a recurring theme in literature. It should be noted that in its natural range (East Asia). *Agrilus planipennis* settles only on dying trees of the genus *Fraxinus* spp. and caused minor damage to viable plants. Y. Dang *et al.* (2021) conducted a retrospective analysis using native range data to identify factors affecting the distribution of invasive wood-boring insects like EAB. Their findings underscore the critical importance of host tree availability and physiological condition in facilitating pest establishment and spread.

Management of invasive species included prevention of arrival. eradication of new populations. biological control. selection of host trees for resistance. and the use of cultural practices (silviculture and restoration) to minimise their impact. In the future. the world's forests were likely to be subjected to an increasing number of invasions. and effective management will require greater international cooperation and interdisciplinary integration. A.M. Liebhold *et al.* (2017) examined the dynamics of invasive species within forest ecosystems, focusing on the ecological, economic, and management challenges posed by such invasions. Their research identified several critical factors that facilitated invasions, including global trade, climate change, and the characteristics of the invaded ecosystems.

Given the sharp decline in the share of ash in forests, UK scientists R.J. Mitchell *et al.* (2014) conducted a special study of the potential loss of ash from the forest. It was found that 955 species were trophically associated with trees of the ash genus *Fraxinus* spp: 12 birds, 28 mammals, 58 bryophytes, 68 fungi, 241 invertebrates, 548 lichens. There were 45 species that occurred only on ash trees, and 62 species that were associated with ash trees and occasionally use other trees, but proved that no other tree species could replace ash for supporting complex trophic chains. Tree species that supported more species associated with ash cannot replace it in terms of ecosystem functions.

As a result of climate change the boundaries of invasive species' ranges have been changing; under favourable conditions, they began to actively increase in number and spread, and with long-term adaptation to local conditions, they were able to maintain a population size sufficient for survival and mass dispersal. N. Puzrina *et al.* (2022) established that outbreaks of stem pests due to extreme temperatures and droughts had been observed in deciduous and coniferous plantations, and according to I. Matsiakh (2019), one of the factors of *Agrilus planipennis* spread was hot summers, which was confirmed by our observations. Further monitoring studies and the search for ways to solve the problem of *Agrilus planipennis* spread were naturally necessary.

Conclusions

Significant weakening of ash trees of the genus *Fraxinus* sp. was noted on the territory of the Botanical Garden of the NULES of Ukraine (21 trees with signs of initial damage, 33 and 23 ash trees moderately and severely damaged, respectively, and 12 trees without signs of damage) and near the stadium (4 trees with signs of initial damage, 28 and 12 common ash trees moderately and severely damaged, respectively). The average number of exit holes ranges from 0.9 to 4.2 per 1 dm^2, which indicates the potential for the species to increase in number. According to the results of determining the species diversity of insects using pheromone traps, it was noted the effectiveness of traps with artificially synthesised pheromones for *Agrilus planipennis*, in all other traps insects of the order *Coleoptera*, which are not potential pests of ash trees *Fraxinus* sp.

Among the promising areas of solving the problem of mass ash drying out, scientists identified the following: search for new methods and means of protecting ash plantations; determination of resistance criteria and selection of plants that were resistant to diseases; development of technologies and production of genetically modified plants with increased resistance.

Invasive insects and diseases could have catastrophic economic and environmental consequences for the structure and functioning of forest ecosystems. They could destroy large areas of forests, leading to loss of biodiversity, changes in the composition of forests and disruption of ecological processes. Therefore, further studies aimed at identifying the peculiarities of the development of the ash narrow-bodied emerald ash borer *Agrilus planipennis* and its distribution were necessary to assess the probability of the species spreading, threats to the condition of plantations, as well as for supervision and control, in particular, with the participation of natural enemies.

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Conflict of Interest

None.

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Інвазія ясеневої смарагдової златки *Agrilus planipennis* Fairmaire, (*Coleoptera: Buprestidae*) на території Національного університету біоресурсів і природокористування (НУБіП) України

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Анотація. Стаття присвячена питанню стрімкого погіршення санітарного стану дерев роду ясен *Fraxinus* sp. на території НУБіП України, спричиненого інвазією ясеневої смарагдової златки *Agrilus planipennis* Fairmaire, (*Coleoptera: Buprestidae*). Мета досліджень оцінка санітарного стану дерев роду ясен *Fraxinus* sp. на території НУБіП України та моніторинг чисельності інвазійного виду *Agrilus planipennis*. Наведено дані інвентаризації 2021-2023 років, де відмічено, що стан 66 % дерев роду ясен характеризується як добрий. Під час проведення детального обстеження 2024 року встановлено стрімке погіршення стану дерев ясеня на всій досліджуваній території. Встановлено, що значне ослаблення дерев роду *Fraxinus* sp. відмічено на території Ботанічного саду НУБіП України та біля стадіону. Відмічаємо, що 13 % дерев без ознак ураження розташовані в глибині лісового масиву, так як для смарагдової златки потенційними живителями є дерева, що ростуть відкрито, хоча за значного розповсюдження комаха може заселяти дерева у глибині насадження. Під час проведення детального лісопатологічного обстеження виявлено імаго *Agrilus planipennis* та характерні D-подібні вильотні отвори. Під час проведення підрахунків кількості типових

D-подібних вильотних отворів на 1 дм^2 визначали щільність поселення та продукцію молодих жуків. Кількість вильотних отворів максимально на 1 дм^2 становить 4,2 ± 1,8, відтак при середній кількості вильотних отворів 1-2,4 на 1 дм^2 протягом 2-3 сезонів може всохнути від 35 до 100 % заселених златкою дерев. Для визначення чисельності та поширення імаго *Agrilus planipennis* проводили обліки за допомогою феромонних пасток з штучно синтезованим феромоном та пастки без використання феромону з приваблюванням комах на колір. За результатами обліків встановлено, що імаго *Agrilus planipennis* наявні тільки у пастках з штучно синтезованими феромонами

Ключові слова: *Fraxinus* sp.; моніторинг; *Agrilus planipennis*; феромонні пастки; інвазійні види

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Sustainable forestry and energy production from biomass: Ecological aspects and dynamics of forest ecosystems

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Abstract. The energy use of forest biomass is an important component of modern bioeconomics, which affects the dynamics of forest cover, the balance of greenhouse gases, and the ecological sustainability of forest ecosystems in regions with active harvesting of wood raw materials. The purpose of the study was to assess the environmental impact of using forest biomass in energy, identifying changes in forest cover, and analysing CO_2 emissions compared to fossil energy sources. A combination of theoretical analysis of literature sources and empirical analysis of Sentinel-2 and Landsat satellite data (2015-2024) was used. A comparative analysis of changes in forest cover is performed using Normalised Difference Vegetation Index and normalised burning ratio indices. CO_2 emissions were calculated based on Intergovernmental Panel on Climate Change emission factors for biomass, coal, and natural gas. In the regions of active biomass use (Amazon, Southeast Asia), forest cover is reduced by 0.8-1.5% annually, while in countries with developed forest policies (Canada, Finland), forest areas remain stable. CO_2 emissions from biomass (112 kg/GJ) are higher than natural gas (56 kg/GJ) but lower than coal emissions (97.5 kg/GJ). Assessment of the relationship between forest ecosystems and climatic factors showed that a reduction in forest cover leads to a loss of water retention capacity (up to 20%) and an increase in soil erosion by 3-4 times. The results of the study confirmed the need to introduce environmentally responsible approaches to Forest Resource Management. The use of

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close-to-nature forestry methods, the development of satellite monitoring, and the introduction of certification standards can contribute to maintaining ecosystem balance

Keywords: satellite monitoring; deforestation; carbon balance; greenhouse gases; climate change; anthropogenic impact

Introduction

Sustainable forest development is one of the key areas of environmental and economic policy in the modern world aimed at supporting the ecosystem functions of forests and the rational use of their resources. Forest ecosystems perform critical functions, including preserving biodiversity, regulating carbon balance and climate processes, maintaining water regimes, preventing soil erosion, and providing material resources for society. However, in the face of increasing anthropogenic stress, climate change and increased demand for renewable energy sources, there is a need to develop effective approaches to forest management that will ensure their rational use without compromising environmental balance.

The use of wood biomass as an energy resource contributes to decarbonising the economy and reducing dependence on fossil fuels but requires compliance with the principles of sustainable forest management. It is important to balance the energy needs and environmental sustainability of forest ecosystems by applying evidence-based approaches to resource base assessment, environmentally sound harvesting methods, and monitoring the long-term effects of bioenergy.

International organisations play an important role in shaping the principles of sustainable forestry and bioenergy development. Food and Agriculture Organization (2024) develops global forest management strategies to reduce forest degradation. European Environment Agency (2024) assesses the impact of forest management on climate and biodiversity by developing recommendations for integrating bioenergy into sustainable development strategies. The UN-sponsored REDD+ programme helps reduce greenhouse gas emissions through forest protection and sustainable use. These initiatives provide a framework for the development of forest bioeconomics and decarbonisation.

Research on sustainable forestry and the use of biomass for energy needs is actively conducted in various regions of the world, which indicates a global interest in the development of bioeconomics and ecosystem conservation (Murtezaj *et al.*, 2024). In the Western Balkans, M. Bojović *et al.* (2024) analysed the potential of agroforestry systems for energy development, emphasising the importance of integrated forest management. In Europe, A. Marín *et al.* (2021) investigated the state of forests, assessing their role in maintaining biodiversity and adapting to climate change. Researchers M. Kocoglu *et al.* (2024), in a global study, evaluated the impact of forest ecosystems on carbon balance, and V. Imbrenda *et al.* (2023) reviewed the socio-economic aspects of forestry in Europe. F. Latterini *et al.* (2023) analysed the current state of forest operations in beech forests in Europe and Western Asia, focusing on the impact of timber harvesting and forest management methods. Approaches to the use of biomass vary by region. The EU, Canada, Sweden, Finland, and the United States are actively developing bioeconomics, making comprehensive use of forest resources. In Brazil and Chile, integrated forestry systems are being implemented that combine timber harvesting with forest restoration. In Central and Eastern Europe, attention is paid to balanced forest management to preserve environmental and economic functions (Vasylyshyn *et al.*, 2023). Evaluating the effectiveness of these approaches and their integration into national energy independence strategies is a critical task.

Current research focused on the transition to sustainable bioeconomics, optimal use of forest resources, and assessment of their environmental impact. L. Prendi & A. Murrja (2023) showed that the integration of a "green" economy contributes to economic growth, but its implementation requires effective regulation and substantial investment in the sustainable management of natural resources. Researchers O. Hoda & G. Angjeli (2023) investigated the dynamics of Environmental growth and established that the successful implementation of bioenergy programmes largely depends on government support and compliance with international standards. Analysis performed by Z. Nedić *et al.* (2024) demonstrated that the transition to circular bioeconomics is possible only if economic incentives are created for enterprises that use low-carbon technologies in the forest and energy sectors. In turn, P. Anttila & H. Verkerk (2022) considered the factors that determine the availability of forest biomass for energy needs, establishing a relationship between the level of harvesting, environmental conditions, and long-term resource sustainability. Authors U. Vilhar *et al.* (2022) analysed the consequences of large-scale forest disturbances, noting that such changes substantially affect hydrological processes, in particular, the balance of karst waters, which can lead to ecosystem degradation.

Despite substantial progress in the examination of bioenergy, the long-term environmental impact of the use of forest biomass, in particular, its role in regulating the carbon balance and changes in forest ecosystems in various climatic conditions, remains insufficiently investigated. The lack of integrated approaches combining satellite monitoring, emission modelling, and sustainable forest management strategies necessitates further scientific development. The aim of the study was to assess the environmental impact of biomass use on energy needs in the context of sustainable forestry, to determine its impact on the dynamics of forest ecosystems, and to analyse changes in forest cover and CO_2 emissions from burning forest biomass. The following tasks were solved to achieve this goal: analyse the principles of sustainable forest resources management and their importance for the conservation of biodiversity and ecosystem services; assess the efficiency of using forest biomass as an energy source based on the analysis of changes in forest cover from satellite images in regions with active use of biomass; calculate the level of CO_2 emissions from burning forest biomass compared to fossil energy sources, which allowed determining the main factors of environmental sustainability of forest bioenergy systems.

Materials and Methods

The research methodology combined theoretical and empirical approaches for a comprehensive analysis of sustainable forestry and the use of biomass in the energy sector. The theoretical part included an analysis of scientific literature and reports of international organisations devoted to forest resource management, bioeconomics, and the environmental impact of biomass use. Special attention was paid to research on the principles of sustainable forest management, the impact of biomass on greenhouse gas balance, and the role of forest ecosystems in maintaining climate balance (Sorge *et al.*, 2022; Favero *et al.*, 2023; Raihan, 2023a). The object of the study was natural and artificially created forest ecosystems used for bioenergy, in particular, boreal, temperate, and mixed forests. The subject of the study is the ecological aspects of the use of biomass for energy needs and their impact on the sustainability of forest ecosystems.

The geographical focus covered regions with active biomass use, in particular, countries of Northern Europe (Sweden, Finland), as well as Canada and the United States, which have substantial forest resources and are actively developing bioenergy. Countries of the Balkan region, in particular, Albania, where harvesting of wood biomass is an important sector of the economy, were also considered. In addition, the study includes regions of Southeast Asia, Central Africa, and the Amazon, as they experience substantial changes in forest cover due to the use of biomass as the main source of energy and the active transformation of natural forests into agricultural land. The choice of territories was driven by their leading role in the development of bioeconomics, the scale of wood biomass harvesting, and the environmental challenges associated with its use, including deforestation of ancient forests, changes in the natural landscape, and carbon emissions from wood processing.

The study was based on the combined use of quantitative and qualitative analysis methods to assess changes in forest cover, the impact of biomass harvesting on forest ecosystems, and greenhouse gas emissions. Iatellite images obtained from the Sentinel-2 missions conducted by the European Space Agency (France) and Landsat-8/9, which are managed by the National Oceanic and Atmospheric Administration and the National Aeronautics and Space Administration (USA), were used to analyse changes in forest cover. The analysis was conducted for the period 2015-2024, which allowed assessing long-term trends in changes in the area of forests used for biomass harvesting and the impact of anthropogenic stress. The images were selected seasonally to avoid the impact of snow cover and ensure the accuracy of calculations. A comparative analysis was performed between the reference years 2015, 2018, 2021, and 2024 to determine the dynamics of changes in forest ecosystems. Satellite images were processed using geoinformation systems ArcGIS (Esri, USA) and Google Earth Engine (Google, USA), which identified changes in forest cover in regions of active biomass harvesting. The use of the Normalised Difference Vegetation Index provided for the estimation of the density of vegetation cover, while the normalised burning ratio was used to determine degraded areas.

The comparative analysis method was used to assess the impact of biomass use on greenhouse gas emissions. CO_2 emissions from burning forest biomass were calculated compared to fossil energy sources such as coal and natural gas. Data for calculations were obtained from open environmental monitoring databases, in particular, the European Environment Agency (2024), Intergovernmental Panel on Climate Change Emission Factors Database (Greenhouse Gas Protocol, n.d.), reports of the International Energy Agency (n.d.). Carbon dioxide emissions were calculated using the formula (1):

$$E = A \times EF, \qquad (1)$$

where E – total CO_2 emissions (tonnes); A – amount of biomass or fossil fuel burned (GJ); EF – emission factor (kg CO_2/GJ), depending on the fuel type. The values of the emission coefficients were taken from the Intergovernmental Panel on Climate Change (2022) database: for wood biomass – 112 kg CO_2/GJ, for coal – 94-101 kg CO_2/GJ, for natural gas – 56 kg CO_2/GJ.

In addition to estimating CO_2 emissions, the study considered the Life Cycle Assessment of biomass, including harvesting, transportation, and incineration processes. This allowed comprehensively assessing the ecological sustainability of forest bioenergy systems, determining their potential for decarbonisation of the energy sector, and assessing the risks of degradation of forest ecosystems as a result of intensive use of wood biomass.

The study was based on the principles of academic integrity and compliance with ethical standards of scientific activity. The use of satellite data and environmental reports was conducted in accordance with open-source licensing requirements.

Results

Sustainable forestry principles and their role in biodiversity conservation

Sustainable forest development is an integral part of global environmental policy aimed at ensuring the long-term use of forest resources while maintaining their environmental sustainability and biodiversity. The main objective is to harmonise the environmental, economic, and social aspects of forest management, which implies compliance with scientifically based principles of sustainable forest management. These include adaptive forest management, reducing the negative impact of timber harvesting on ecosystems, introducing methods for restoring forest areas, and preserving biodiversity through the introduction of regulatory and certification mechanisms (Raihan, 2023b).

One of the most important principles is to ensure ecosystem balance through environmentally responsible logging. The introduction of selective and Mosaic logging instead of continuous logging reduces habitat loss for rare species of flora and fauna. In the Scandinavian countries, in particular, in Sweden and Finland, the approach of "Close-to-Nature Forestry" has long been used, which involves maintaining the natural composition of forests, using mixed plantings and gradual logging that does not disrupt the ecosystem balance (Favero *et al.*, 2023). This approach is also actively used in Germany, where research has shown its positive impact on biodiversity and maintaining the sustainability of forest ecosystems (Sorge *et al.*, 2022).

Another important aspect of sustainable forest management is certification systems, such as the Forest Stewardship Council and the Programme for the Endorsement of Forest Certification, which define environmental standards for logging companies. In Canada and the United States, more than 80% of industrial forests are subject to these standards, which allows controlling the level of deforestation and restoration of forest areas. In developing countries, in particular, in Latin America and Southeast Asia, certification is less widespread, which creates risks for forest ecosystem services and contributes to illegal logging (Huettmann & Young, 2022).

Biodiversity conservation also depends on measures to restore degraded forest areas. In the countries of the European Union, reforestation programmes are being implemented aimed at restoring natural tree species and the ecosystem functions of forests. For example, the EU Biodiversity Strategy 2030 initiative provides for increasing the area of protected forests and restoring disturbed ecosystems (European Commission, n.d.). Similar programmes are being implemented in the United States and Canada, where government support is aimed at the afforestation of territories after forest fires and anthropogenic deforestation (Favero *et al.*, 2020).

Modern satellite monitoring methods and geographic information systems are widely used for effective forest management. Satellite images Sentinel-2 and Landsat-8/9 are used to analyse changes in forest cover and assess the level of forest degradation as a result of biomass harvesting. Analysis of satellite data for the period 2015-2024 indicates substantial loss of forest cover in areas of intensive forest management, especially in the rainforests of Southeast Asia and the Amazon, where deforestation has a substantial impact on the global balance of CO_2 emissions. Additionally, the geoinformation systems ArcGIS (Esri, USA) and Google Earth Engine are used to identify long-term trends in forest cover changes, assess the level of recovery, and form recommendations for sustainable forest management policies.

Sustainable forest development is based on the introduction of environmentally responsible forest management approaches that consider biodiversity conservation, ecosystem services support, and biomass management (Table 1).

Table 1. Basic principles of sustainable forestry and their implementation in different regions of the world

Principle	Description	Implementation example
Biodiversity conservation	Restriction of deforestation in natural forests, creation of nature protection zones	Forest Stewardship Council certification in Canada, USA
Restoration of forest ecosystems	Afforestation programmes, support for natural renewal	EU Biodiversity Strategy 2030
Close-to-nature Forestry	Use of mixed plantings, selective logging, forest structure regulation	Forestry practices in Finland, Sweden, Germany
Monitoring by satellite systems	Analysis of changes in forest cover and assessment of degradation	Sentinel-2, Landsat-8/9

Source: compiled by the authors based on analysis of the data A. Favero *et al*. (2020; 2023), S. Sorge *et al*. (2022)

These tables show substantial variability in approaches to implementing the principles of sustainable forestry in different regions of the world. Differences in environmental conditions, economic opportunities, and legal requirements affect the nature of forest management strategies. For example, countries with developed environmental regulation systems are more effective in implementing certification systems and satellite monitoring, while regions with high anthropogenic pressure are dominated by measures to restore forest ecosystems. An important factor is the adaptation of close-to-nature forestry methods to local conditions, which allows for a balance between economic benefits and environmental sustainability. The use of technological solutions, such as satellite monitoring, contributes to more accurate monitoring of forest conditions, but its effectiveness depends on political will and institutional support at the national level (Moroz, 2024).

Applying the principles of sustainable forestry is a critical tool for preserving biodiversity and ensuring the long-term ecological sustainability of forest ecosystems. Regional differences in the implementation of these principles indicate the need to adapt management methods to local conditions, considering economic, climatic, and social factors. The integration of modern technologies, such as satellite monitoring and certification systems, allows effectively assessing the state of forests and optimise their use. An integrated approach to forest management, combining environmental, economic, and social aspects, is a prerequisite for achieving sustainable forest sector development.

Use of biomass for energy production and efficient forest management

Forest biomass is an important component of renewable energy, helping to reduce dependence on fossil fuels and providing opportunities for decarbonisation of the energy sector. The use of wood biomass for energy production includes burning wood residues, processing wood into pellets, and producing synthetic fuels. However, the effectiveness of bioenergy largely depends on regional approaches to forest management, in particular, the level of forest regeneration, environmental monitoring, and sustainable forest management policies (Golub *et al.*, 2017).

Estimating CO_2 emissions from biomass use is a critical factor when comparing it with traditional energy sources. Despite the fact that wood is considered a carbon-neutral fuel, the processes of its harvesting, transportation, and incineration are accompanied by greenhouse gas emissions. According to the Intergovernmental Panel on Climate Change (2022) database, the average level of CO_2 emissions from burning wood biomass is 112 kg of CO_2/GJ, which is higher than that of natural gas (56 kg of CO_2/GJ) but lower than that of coal (94-101 kg of CO_2/GJ). Formula (1) was used to estimate carbon emissions in forest bioenergy systems, which accounts for the level of energy consumption and the corresponding Intergovernmental Panel on Climate Change coefficients (Fig. 1).

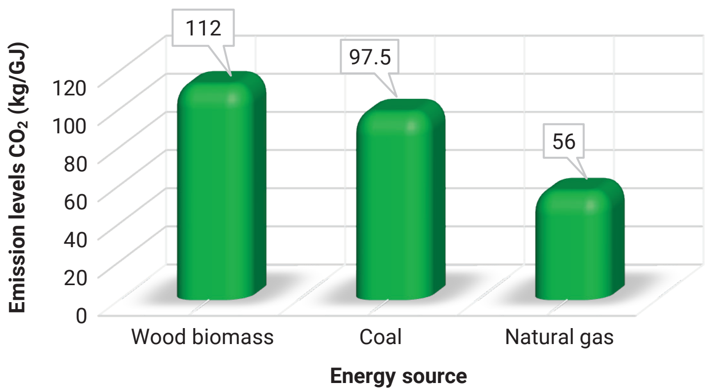

Figure 1. Comparison of CO_2 emissions from different energy sources (kg CO_2/GJ)
Source: compiled by the authors based on analysis of the Intergovernmental Panel on Climate Change (2022)

The comparison results show that the use of wood biomass for energy production has both advantages and limitations. The main argument in favour of biomass is its potential carbon neutrality since trees absorb CO_2 during growth, compensating for emissions from combustion. However, this effect is achieved only if the principles of sustainable forest management are observed and the balance between harvesting and forest regeneration is maintained.

Studies show that the efficiency of biomass as an energy source is highly dependent on regional conditions. For example, in the Scandinavian countries and Canada, effective forest resource management models have been implemented, which allows maintaining a balance between biomass harvesting and natural forest restoration. In countries with less developed environmental regulatory systems, intensive use of wood biomass can lead to loss of forest cover and reduced ecosystem functions. Additional analysis allowed assessing the potential sustainability of bioenergy systems compared to other fuels and comparing key indicators of biomass efficiency compared to other energy sources (Table 2).

Table 2. Comparative analysis of the efficiency of using biomass and other fuels

Indicator	Biomass	Coal	Natural gas	Solar energy
CO_2 emissions (kg/GJ)	112	97.5	56	0
Energy efficiency ratio (%)	35-45	33-38	45-50	18-22
Resource availability	Renewable	Limited	Limited	Unlimited
Environmental impact	Affects forests	High impact	Moderate impact	Minimal impact

Source: compared by the authors based on the analysis of data from European Environment Agency (2024), Intergovernmental Panel on Climate Change (2022), International Energy Agency (n.d.)

Analysis of the efficiency of using biomass for energy production has shown that it can be an alternative to fossil fuels, but its sustainability depends on compliance with environmental principles. CO_2 emissions from biomass remain higher than those of natural gas but lower than those of coal. Therewith, the life cycle of biomass considers forest regeneration, which potentially reduces its environmental impact. Regional approaches to the use of biomass play a crucial role in its efficiency. Countries with developed forest policies perform substantially better in balancing the use of biomass and ecosystem conservation. Technological development is also an important factor: the combined use of biomass and solar energy can ensure a stable supply of renewable energy with minimal impact on the environment.

The use of wood biomass as an energy source is an important area of renewable energy development, but its effectiveness largely depends on the rational management of forest resources. The results of the study show that a balanced approach to the harvesting and use of biomass can help reduce greenhouse gas emissions and, at the same time, prevent the depletion of forest ecosystems. Innovative methods for monitoring forest cover, regulating wood harvesting, and introducing environmentally friendly biomass processing technologies are instrumental in this process. Optimising these processes will reduce environmental risks and improve the efficiency of the bioenergy sector in the context of global decarbonisation.

Dynamics of changes in forest cover and its environmental consequences

Changes in forest cover reflect the balance between the processes of restoration and degradation of forest ecosystems, determining their resistance to anthropogenic and natural factors. The assessment of changes in forest area was based on an analysis of Sentinel-2 and Landsat-8/9 satellite images over four reference years: 2015, 2018, 2021, and 2024. The use of satellite data allowed analysing long-term changes in forest areas in regions of active biomass harvesting and identifying areas with an increased risk of degradation.

In the period 2015-2024, a gradual reduction in Woodlands was recorded, which is confirmed by the analysis of the Normalised Difference Vegetation Index and the normalised burning ratio. The greatest loss of forest cover was observed in tropical regions, where Normalised Difference Vegetation Index levels were 18% lower in 2024 compared to 2015, indicating intense ecosystem degradation. Thereby, in temperate latitudes, the reduction in forest area during this period ranged from 6% to 10%, depending on the level of wood biomass harvesting and the implementation of forest restoration policies. Data for individual reference years reveal a gradual increase in the intensity of logging. In 2018, forest area losses compared to 2015 amounted to 3.4%, while in 2021, this figure reached 7.8%. The latest analysis for 2024 confirmed further forest declines, especially in regions with high levels of industrial forest use, such as the Amazon, Central Africa, and Southeast Asia.

A comparison of changes in the normalised burning ratio index shows an increase in the number of degraded forest plots. If in 2015 this indicator was stable, then in 2018 it grew by 5%, in 2021 – by 9%, and in 2024 – by 13%. This confirms an increase in deforestation, forest fires, and other processes that contribute to ecosystem destruction. Forest areas bordering agricultural land and areas with a high level of urbanisation were particularly vulnerable. In the Amazon basin, active deforestation leads to a decrease in humidity levels and an increase in the frequency of fires, which further accelerates the degradation processes (Raj *et al.*, 2023). In Indonesia and Malaysia, the deforestation of tropical forests is associated with the expansion of oil palm plantations, which leads to the loss of unique biotopes and negatively affects local ecosystems (Farooq *et al.*, 2022). In Europe, forest degradation is most intensively observed in the Carpathians, where the reduction of continuous forest areas threatens biodiversity and ecosystem functioning (Fatima *et al.*, 2024).

Analysis of satellite images and geoinformation systems ArcGIS, Google Earth Engine also allowed evaluating the effectiveness of forest conservation and restoration measures. The data show that regions where active reforestation programmes are being implemented demonstrate stabilisation or even a slight increase in forest cover. For example, in Northern Europe and Canada, forest areas in 2024 remained virtually unchanged compared to 2015, which is due to the introduction of strategies for close-to-nature forestry and control over logging activities (Salam, 2024). Such technologies provide a comprehensive approach to the analysis of ecosystem changes and help model scenarios for further forest development under the influence of climate change and anthropogenic factors (Fig. 2).

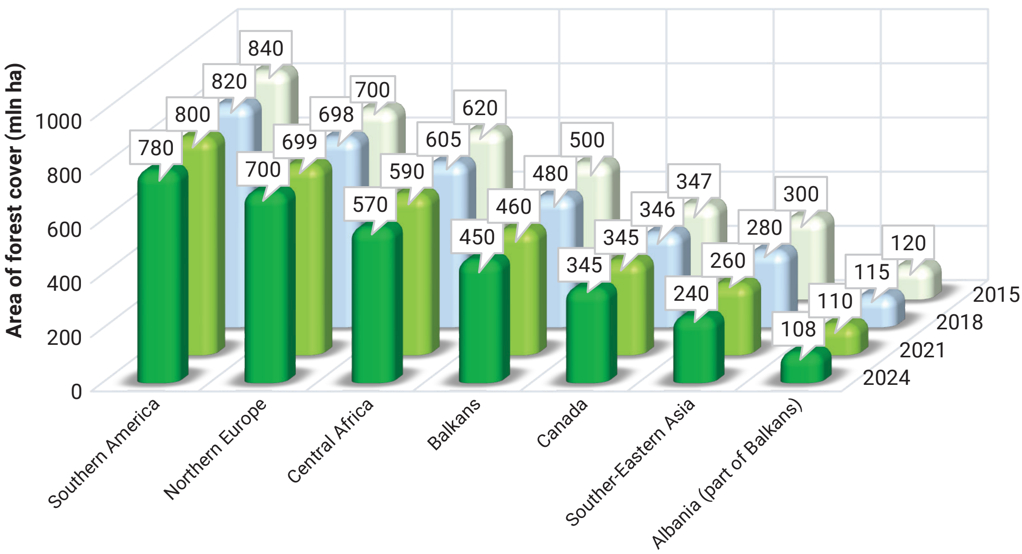

Figure 2. Changes in forest cover in selected regions (2015-2024)
Source: compared by the authors

The graph presents substantial regional differences in forest cover changes over the period 2015-2024, reflecting different levels of Environmental Management and approaches to sustainable forest management. In Northern Europe and Canada, forest areas remained stable due to the introduction of nature conservation and logging controls. Thereby, a substantial reduction in forest cover in the regions of Southeast Asia indicates the intensive exploitation of forest resources for agriculture and energy, which has serious environmental consequences. The Balkans are experiencing a gradual reduction in forest cover due to timber harvesting and the expansion of agricultural land (Bragina *et al.*, 2018). In Albania, as part of the Balkan region, forest cover is also decreasing, which may be due to illegal logging and increased use of wood for energy purposes, despite the implementation of forest restoration programmes (Shumka *et al.*, 2021).

The identified trends highlight the importance of strengthening international cooperation in the field of forest conservation and introducing stricter regulatory mechanisms for controlling logging. In addition, the results obtained confirm the need to develop adaptive forest ecosystem management strategies that consider both environmental and socio-economic factors.

Interaction of forest ecosystems with other natural processes and ecological balance

Forest ecosystems are important regulators of global ecological processes, in particular, the carbon cycle, hydrological balance, and soil cover stability, ensuring the resilience of the biosphere to external changes. One of the main functions of forests is the accumulation and conservation of carbon, which is conducted through the processes of photosynthesis, the accumulation of organic matter, and carbon deposition in the soil. Forests absorb about 2.6 billion tonnes of CO_2 annually, which is equivalent to 30% of anthropogenic greenhouse gas emissions (Ibrahim & Lukman, 2022). The largest carbon reserves are found in the Amazon, Congo, and Indonesia rainforests, but their destruction due to logging and land-use changes leads to CO_2 emissions because of the mineralisation of organic matter (Bălan *et al.*, 2021).

In addition to regulating carbon balance, forests play a fundamental role in water conservation. They retain moisture, regulate the amount and quality of water in catchment areas, affect groundwater levels, and prevent the degradation of aquatic ecosystems. Changes in forest cover can lead to changes in hydrological cycles, which is confirmed by studies on the relationship between forest ecosystems and water resources in Europe, North America, and Asia. Deforestation in mountainous areas leads to an increase in erosion processes, which in turn worsens water quality and reduces its natural filtration potential (Anderson-Teixeira *et al.*, 2013; Dunlap & Schramski, 2024).

Another important ecological process that depends on the state of forests is the protection of soil from erosion. The root system of trees prevents soil erosion, reduces the risk of landslides, and preserves land fertility. In countries with a high level of erosion hazard, in particular, in southern Europe, afforestation programmes are used to stabilise soils and reduce the negative effects of water and wind erosion (Wani & Sahoo, 2021). The impact of forest ecosystems on soil conservation is particularly important in agricultural regions, where land degradation can lead to reduced yields and the deterioration of agricultural landscapes (Melo *et al.*, 2021).

Climate change has a substantial impact on the stability of forest ecosystems, increasing the risks of pest spread, the frequency of fires, and changes in species composition. According to forecasts, an increase in average annual temperatures and changes in precipitation can affect the stability of forests in the middle and northern latitudes, causing a decrease in forest productivity and loss of biodiversity (Baciu *et al.*, 2021; Grebner *et al.*, 2021). It is necessary to introduce approaches to nature forestry, increase the diversity of tree species, and develop strategies for adapting to extreme weather conditions to adapt forest ecosystems to climate change. The interaction of forests with natural processes forms mechanisms of ecological stability that affect CO_2 emissions, hydrological cycles, and soil stability (Table 3).

Table 3. Relationship between forest ecosystems, carbon balance, water regime and erosion processes in different regions of the world

Region	Biomass carbon Reserve (MT/ha)	Water retention capacity of forests (mm/year)	Soil erosion rate (t/ha/year)
Amazon	230	850	0.5
Northern Europe	150	780	2.1
Central Africa	220	810	0.5
East Asia	170	690	3.5
Southeast Asia	190	720	2.9
Canada	180	760	1.8
United States (continental)	160	700	2.6
Australia	140	670	3.9

Source: compiled by the authors based on analysis of the data E.M. Bălan *et al*. (2021), A. Ibrahim & A.H. Lukman (2022)

These tables present substantial regional differences in the ability of forest ecosystems to maintain carbon balance, regulate water regimes, and prevent soil erosion. High water retention capacity and carbon storage are characteristic of rainforests, which ensures their important role in global climate processes. However, in regions with active anthropogenic impact, in particular, in areas of intensive forest management, there is increased soil erosion, which can negatively affect the productivity of ecosystems and the sustainability of local water resources. The identified patterns highlight the importance of adaptive forest management strategies aimed at minimising degradation processes and maintaining the stability of natural systems.

The results confirm that forest ecosystems are an important regulator of natural processes, ensuring carbon balance, water stability, and soil protection from erosion. Analysis of regional features shows that the effectiveness of these functions depends on climatic conditions, the type of forest, and the level of anthropogenic impact, which highlights the need for an adaptive approach to forest management. Implementing sustainable forest management strategies can help strengthen ecosystem balance, minimise the negative impact of climate change, and preserve critical ecosystem services.

Recommendations for optimising the use of forest biomass in the context of climate change

The use of forest biomass as a renewable energy source plays an important role in the global decarbonisation strategy, but the effectiveness of its application largely depends on forest management methods. In the face of climate change, it is necessary to introduce integrated approaches to biomass harvesting that will contribute to the conservation of biodiversity and ecological sustainability of forest ecosystems. It is proved that sustainable development of the forest sector is possible only if ecosystem approaches to forest management are integrated, including adaptation to extreme climatic phenomena, improving resource efficiency, and introducing innovative wood processing technologies (Baciu *et al*., 2021).

Climate change has a substantial impact on forest ecosystems, causing changes in temperature and precipitation regimes, the spread of pests, an increase in the frequency of fires and forest degradation. Studies show that an increase in the average annual temperature by 1.5-2°C over the next decades can substantially reduce the productivity of forests in the middle and northern latitudes. In addition, climate change affects the carbon balance: reduced forest cover and increased carbon load due to frequent fires can lead to a loss of the natural ability of forests to absorb CO_2 (Table 4).

Table 4. Impact of climate change on forest ecosystems in different regions of the world

Region	Main climate changes	Impact on forests	Possible adaptation measures
Amazon	Reduced precipitation, increased periods of drought	Increased frequency of forest fires, rainforest degradation	Expansion of afforestation programmes, fire control
Northern Europe	Rising temperatures, increasing storms	Increased damage from hurricanes, pest spread	Strengthening selective forestry, monitoring forest health
Central Africa	Increase in the average annual temperature	Reduced tree growth, reduced biomass	Use of drought-resistant species, forest reclamation
East Asia	Uneven precipitation, monsoon changes	Increased risk of soil erosion and flooding of woodlands	Engineering soil protection, flood control
Canada	Reducing the freezing period of soils	Loss of boreal forests, migration of tree species	Transition to more sustainable forest species

Source: compiled by the authors based on analysis of the data D.L. Grebner *et al*. (2021), A. Kumar *et al*. (2022)

These tables indicate substantial variability in the impact of climate change on forest ecosystems depending on the region. In tropical and subtropical forests, rising temperatures and changes in humidity conditions cause biodiversity degradation and increase the risk of forest fires. In temperate climates, the main threats are changes in the structure of forest stands and the spread of pests, while in arid regions such as Australia, there is an increase in the frequency of catastrophic fires.

One of the key areas of adaptation of the forest sector is the introduction of principles of close-to-nature forestry. This includes maintaining mixed plantings, selective logging, and regulating the age structure of woodlands. Such methods can reduce the impact of logging on the environment, improve the restoration of stands, and increase the resistance of forests to droughts, diseases, and pests (Hernández-Morcillo *et al*., 2022). In addition, it is important to expand the use of agroforestry – the integration of forest ecosystems into agricultural landscapes. This will help increase the sustainability of forest systems, minimise degradation risks, and provide additional sources of biomass without putting excessive strain on natural forests (Raihan, 2023a).

The development of technologies for generating energy from biomass plays an essential role in improving the efficiency of resource use. The use of cogeneration plants, the biochemical processing of wood biomass, and advanced gasification technologies can increase the efficiency of biofuel systems and reduce CO_2 emissions (Tampekis *et al*., 2024). Another important area is the introduction of certification standards for sustainable forest management, such as Forest Stewardship Council and Programme for the Endorsement of Forest Certification, which guarantee the environmental responsibility of bioenergy companies (Mishra & Agarwal, 2024). This contributes to the transparency of the biomass market and ensures the environmental compliance of production.

Adapting the forest sector to climate change requires an integrated approach, including the introduction of environmentally friendly harvesting methods, the development of monitoring systems, and increased regulation in the field of forest management. It is important to ensure a balance between the energy potential of forest biomass and the preservation of the ecosystem functions of forests. The introduction of modern bioenergy technologies and improved sustainable development policies will help reduce greenhouse gas emissions and supplement the resilience of forest resources to climate change. The implementation of these measures will ensure the long-term stability of the bioenergy sector and contribute to the efficient use of natural resources.

Discussion

The results show substantial variability in approaches to forest management and biomass use, which is confirmed by a comparative analysis with other studies. Comparing the obtained data with the scientific works of international researchers allows identifying general trends and conflicting aspects regarding the environmental sustainability of forest management.

Examination of the efficiency of using biomass for energy needs has shown that its potential largely depends on regional forest management strategies. Similar conclusions were drawn by A. Favero *et al*. (2023), who emphasise the need to integrate bioenergy into the overall decarbonisation policy, nevertheless note that uncontrolled harvesting of wood biomass can lead to negative environmental consequences. The results obtained confirm this statement because the analysis of satellite images indicates a decrease in the area of forest cover in regions of intensive biomass use. A. Favero *et al*. (2020) demonstrate that, despite the reduction of forest areas, their role in carbon sequestration remains substantial if sustainable forest management measures are implemented.

The study confirmed that the effective use of forest biomass as an energy resource directly depends on forest ecosystem management strategies and forest restoration measures. The results prove that regions with clear mechanisms for controlling and regulating logging have a higher level of forest cover conservation, which is consistent with the findings of T. Farooq *et al*. (2022), which established a relationship between the intensity of wood biomass harvesting and the spatial distribution of carbon in forest ecosystems. Similar conclusions were drawn by S. Fatima *et al*. (2024), noting the importance of an integrated approach to agroforestry to ensure the sustainability of the bioenergy sector.

In matters of forest ecosystem management, the results of the analysis partially coincide with the conclusions of S. Sorge *et al*. (2022), emphasising the importance of socio-ecological aspects in forest management. The authors state that the lack of an integrated approach to forest management can lead to a conflict between economic and environmental goals. This study supports this thesis, as the regions with active logging have a higher level of soil erosion and a lower ability of forests to retain moisture. In addition, A. Raihan (2023b) underlines that the sustainability of the forest sector is determined not only by economic incentives but also by policy decisions and the availability of effective environmental programmes.

Regarding the changes in forest cover, the results are consistent with the conclusions made by F. Huettmann & B. Young (2022) that modern approaches to able forestry are not always effective since they allow the depletion of natural forests even in certified regions. This study showed that regions with active implementation of close-to-nature forestry, such as Scandinavia, have shown a stable level of forest cover over the past decade. This confirms the hypothesis put forward by A. Raj *et al*. (2023) that adaptive forest management is a fundamental factor in maintaining their ecological balance.

The assessment of CO_2 emissions from burning forest biomass compared to fossil fuels confirmed that bioenergy can play a positive role in reducing carbon emissions only if the scale of harvesting is strictly controlled and forest resources are effectively managed. This is consistent with the results of A. Salam (2024), stressing the role of digital technologies and remote monitoring tools in optimising the use of woodlands. Similar conclusions are presented in a paper of A. Ibrahim & A. Lukman (2022), which emphasises the need to estimate carbon reserves in biomass to determine its real potential as an energy source. The results of the analysis of the impact of large-scale biomass harvesting on the ecological balance of forest ecosystems showed an increase in the level of soil degradation and changes in the water regime in regions with high logging intensity. Findings alike were discovered by E. Bălan *et al*. (2021), investigating the impact of agricultural and bioenergy activities on the state of forest landscapes. J. Dunlap & J. Schramski (2024) confirm that estimating biomass losses that can store carbon in the long term is crucial for developing strategies for the environmentally sustainable use of forest resources. An assessment of the impact of changes in forest cover on the water balance and carbon cycle has shown that forest ecosystems are important regulators of greenhouse gas emissions and water regimes, which is consistent with the statement of F. Melo *et al*. (2021). A study by these authors confirmed that changes in forest cover substantially affect the relationship between water, energy, and food resources. In turn, G. Baciu *et al*. (2021) focus on the need to integrate the economic and environmental aspects of forest ecosystem services assessment, which correlates with the data obtained on the substantial impact of large-scale logging on the stability of natural processes.

The study on the dynamics of changes in forest cover and its ecological functions confirmed the importance of integrated approaches to forest ecosystem management. Analysis of satellite data and vegetation indices showed a close relationship between anthropogenic impact, climate change, and forest bioproductivity, which is consistent with the results of K. Anderson-Teixeira *et al*. (2013), who determined that climate change affects the dynamics of forest restoration, slowing their growth and changing the structure of ecosystems. Similar conclusions were drawn by A. Wani & G. Sahoo (2021), highlighting the critical role of forests in maintaining biodiversity and the stability of ecosystem processes. The results of the forest management effectiveness study indicated that regions with a high level of use of geoinformation technologies and monitoring systems show lower rates of degradation of forest ecosystems, which is consistent with the conclusions of D. Grebner *et al*. (2021). A study by A. Kumar *et al*. (2022) also affirms that the introduction of geoinformation technologies, satellite monitoring, and algorithms for assessing the state of forests helps to reduce the risks of ecosystem degradation and increases the efficiency of forest management. The use of integrated spatial data analysis models makes it possible to predict changes in forest cover and their consequences for ecosystem services, which is confirmed by M. Hernández-Morcillo *et al*. (2022).

The results of this study also showed that adaptive measures for the sustainable use of biomass and the prevention of negative environmental impacts are critical to maintaining the sustainability of forest ecosystems. This is supported by a publication by A. Raihan (2023b), who analysed integrative approaches to the assessment of ecosystem services and proved the importance of combining environmental, social, and economic aspects in forest management. Thereby, S. Tampekis *et al*. (2024) note the need to improve forest management planning to increase the resilience of forest landscapes to climate change, which is confirmed by the data obtained in this study. The assessment of forest restoration measures and the reduction of the impact of logging activities on ecosystems confirmed the effectiveness of programmes aimed at afforestation and the natural renewal of forests (Ivanyuk *et al.*, 2024). This is in line with the results of R. Mishra & R. Agarwal (2024), who review approaches to restoring degraded forests and argue that long-term adaptive management strategies ensure environmental stability. A similar conclusion was achieved by E. Nungula *et al*. (2024), who proved that the combination of forest and agroforestry management contributes to improving soil quality and water balance.

The review of the effectiveness of modern forest management technologies also revealed that the use of automated systems for planning and forecasting the dynamics of forest ecosystems improves the efficiency of biomass harvesting and reduces environmental risks. The findings of A. McEwan *et al.* (2020), who analysed the prospects for industrial forestry and emphasised the importance of innovative approaches in planning logging operations, support this statement. R. Gupta & L. Sharma (2019) confirmed that the use of process-oriented models, such as 3-PG, allows predicting the growth of forest ecosystems, optimising management decisions, and ensuring a balance between biomass harvesting and forest conservation. The results of the study also confirmed the importance of a trade-off between biomass production and biodiversity conservation, which correlates with the findings of J. Rybar & M. Bosela (2023), who analysed the correlation between the intensive use of forest resources and the conservation of natural ecosystems in Europe.

Summarising the results of the study showed that effective forest management requires a balance between environmental sustainability, economic interests, and the impact of climate change. The analysis confirmed the correlation between the introduction of sustainable forest management methods and the reduction of the negative impact of the bioenergy sector on forest ecosystems. Comparison with other studies has shown that the use of technological solutions, adaptive forestry, and integrated approaches to biomass management contributes to the conservation of biodiversity and the maintenance of natural processes. The results obtained are consistent with the conclusions of international scientific papers and emphasise the need for further research in the direction of optimising the use of forest biomass in the context of climate change.

Conclusions

The study allowed assessing the impact of sustainable forestry and biomass use on ecological balance and identifying trends in changes in forest ecosystems in the context of climate change and the growth of the bioenergy sector. Analysis of current approaches to forest management has shown that the most effective strategies include limiting deforestation in natural forests, creating protected areas, certifying forest products (Forest Stewardship Council, Programme for the Endorsement of Forest Certification), and taking measures for active forest restoration. In regions where close-to-nature forestry has been introduced, forest areas remain stable or show a tendency to recover, for example, in Canada and the Nordic countries.

Comparison of CO_2 emissions with different energy sources confirmed that burning wood biomass (112 kg CO_2/GJ) generates less greenhouse gases compared to coal (average 97.5 kg CO_2/GJ) but more than natural gas (56 kg CO_2/GJ). However, the long-term balance of emissions depends on the level of forest restoration: in countries with high standards of forest management (Sweden, Finland), the level of biomass harvesting is compensated by the natural reproduction of forest ecosystems.

Dynamics of changes in forest cover and its environmental consequences Based on the analysis of Sentinel-2 and Landsat satellite images for the period 2015-2024, it was determined that in tropical regions such as the Amazon and Southeast Asia, forest areas decreased by 0.8-1.5% annually due to intensive biomass harvesting and land use changes. Therewith, in the European Union and Canada, forest areas remained stable or showed an increase of 0.2-0.5% because of the afforestation and natural renewal programmes.

Forest ecosystems perform crucial functions in maintaining climate stability. Carbon reserves in biomass vary substantially depending on the region: in the Amazon, this figure reaches 230 MT/ha, while in Northern Europe – 150 Mt/ha. Thereby, the water retention capacity of forests is crucial for maintaining water balance, especially in regions with arid climates such as Australia (670 mm/year). It was established that the loss of forests in tropical regions leads to an increase in the level of soil erosion by 3-4 times, which leads to land degradation and a decrease in their productivity.

Optimising the use of forest biomass in the face of climate change requires combining sustainable harvesting methods with effective forest management policies. The introduction of low-emission technologies for biomass processing and an increase in the share of fast-growing tree crops will help reduce the environmental burden. The expansion of satellite monitoring will provide for a more accurate monitoring of the dynamics of changes in forest cover, and economic incentives for certified forestry will increase environmental responsibility. Further studies should include more detailed regional estimates and use multi-year carbon balance data. It is also important to consider the socio-economic factors that affect the development of the bioenergy sector and its impact on the environment.

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Conflict of Interest

None.

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Стале лісове господарство та виробництво енергії з біомаси: екологічні аспекти та динаміка лісових екосистем

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Анотація. Енергетичне використання лісової біомаси є важливою складовою сучасної біоекономіки, яка впливає на динаміку лісового покриву, баланс парникових газів та екологічну стійкість лісових екосистем у регіонах з активною заготівлею деревної сировини. Метою дослідження є оцінка екологічних наслідків використання лісової біомаси в енергетиці, виявлення змін у лісовому покриві та аналіз викидів CO_2 порівняно з викопними джерелами енергії. Використано поєднання теоретичного аналізу літературних джерел та емпіричного аналізу даних супутників Sentinel-2 та Landsat (2015-2024 рр.). Порівняльний аналіз змін лісового покриву виконано з використанням індексів нормалізованого різницевого вегетаційного індексу та нормалізованого коефіцієнта випалювання. Викиди CO_2 розраховані на основі коефіцієнтів викидів Міжурядової групи експертів зі зміни клімату для біомаси, вугілля та природного газу. У регіонах активного використання біомаси (Амазонія, Південно-Східна Азія) лісистість скорочується на 0,8-1,5 % щорічно, тоді як у країнах з розвиненою лісовою політикою (Канада, Фінляндія) лісові площі залишаються стабільними. Викиди CO_2 з біомаси (112 кг/ГДж) вищі, ніж з природного газу (56 кг/ГДж), але нижчі, ніж з вугілля (97,5 кг/ГДж). Оцінка взаємозв›язку між лісовими екосистемами та кліматичними факторами показує, що зменшення лісистості призводить до втрати водоутримуючої здатності (до 20 %) та збільшення ерозії ґрунтів у 3-4 рази. Результати дослідження підтверджують необхідність впровадження екологічно відповідальних підходів до управління лісовими ресурсами. Використання наближених до природи методів ведення лісового господарства, розвиток супутникового моніторингу та запровадження стандартів сертифікації можуть сприяти збереженню екосистемної рівноваги

Ключові слова: супутниковий моніторинг; вирубка лісів; вуглецевий баланс; парникові гази; зміна клімату; антропогенний вплив

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Impact of global climate change on the biological characteristics of tree species in forest ecosystems

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Abstract. The purpose of this study was to analyse physiological and morphological changes in the most common woody species of the forest ecosystem under the influence of climate change and to investigate the adaptive mechanisms that these species use to overcome stressful weather conditions. The study examined the impact of global climate change on the biological characteristics of Scots

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pine, northern red oak, and silver birch. In particular, the adaptive mechanisms of trees that allow them to survive and adapt to changing conditions were analysed. The influence of an increase in average temperature, changes in precipitation regimes, and extreme weather events on the growth, development, and reproduction of woody plants was considered. Field monitoring methods and laboratory experiments were used to collect data on physiological and morphological changes that occur with tree species groups under the influence of climatic pressure. The results of the study showed that global climate change can lead to significant changes in the species composition of forests, their productivity and overall environmental sustainability. The findings highlight the need for adaptive strategies for forest management and biodiversity conservation in the face of global climate change. The study also examined guidelines for practical actions aimed at mitigating the negative effects of climate change on forest ecosystems. The vulnerability of Ukrainian forests to climate change in the 21st century in comparison with the climate norm (1961-1990) was assessed. Recommendations for assessing the impact of climate change on forests, analysing phytodiversity and environmental regimes based on forest monitoring data in the context of regulatory legal acts of Ukraine, in particular, the state forest management strategy until 2035 and recommendations of the state forest cadastre of Ukraine are provided. The results of the study can be used to develop forest management strategies, implement adaptation measures in forestry, and to monitor the state of forest ecosystems and predict their resilience to climate change within the framework of national environmental programmes

Keywords: climate pressure; biodiversity; physiological changes; forest productivity; ecosystem monitoring; adaptation mechanism

Introduction

The urgency of climate change is extremely high at the global level, as it directly affects the state of natural ecosystems and their functions. Climate change, including rising average temperatures, changes in precipitation patterns, and the frequency and intensity of extreme weather events, significantly affect the biological characteristics of many ecosystems, particularly forest ecosystems, where tree species play a key role in maintaining biodiversity, regulating water balance, and influencing the carbon cycle.

In this context, the study of the impact of global climate change on the biological characteristics of tree species is of critical importance for ensuring ecosystem stability and sustainable development. In the context of globalisation and intensive use of natural resources, understanding the dynamics of ecosystem responses to climate change is essential for developing effective adaptation strategies and management measures (Floqi *et al*., 2009).

Scientific research in this area is of great importance not only for expanding theoretical knowledge, but also for practical solutions that can contribute to the preservation of the biogeocoenosis in changing climatic conditions. Research on the impact of climate factors on ecosystems is conducted in various scientific disciplines, such as ecology, botany, climatology, and agronomy.

I. Buksha *et al*. (2023) emphasised the importance of monitoring environmental changes, highlighting the development of adaptation strategies for tree species in the face of increasing climate stress. M.M. Radomska *et al*. (2022) investigated the relationship between climate factors and plant biodiversity, noting that changes in temperature and humidity can significantly affect the structure and function of natural communities, in particular forest ecosystems, including protected ones, which leads to a decrease in species diversity. A.A. Miniaylo *et al*. (2014) focused on the analysis of the impact of climate change on forest ecosystems in Ukraine, the development of measures to reduce their negative impact, and adaptation of forest stands through improved resource management, selection of sustainable tree species, forest restoration, and economic assessment of the risks and opportunities arising from these changes. O. Furdychko *et al*. (2021) argued in their paper that climate is one of the most powerful environmental factors determining the evolution of the biosphere and the organic world.

Z.M. Budnik *et al*. (2023) investigated the impact of environmental factors on forest ecosystems in Ukraine to predict the amount of forest resources for forestry and woodworking industries. This allows for the development of measures to prevent climate change and adapt forests, which helps to assess the productivity and condition of forests in the medium and long term. These studies confirm the need for an urgent response in the natural resource management system.

Studies of the forest-steppe zone of Ukraine illustrate how different tree species adapt to specific regional conditions (Furdychko *et al*., 2021). For example, Scots pine (*Pinus sylvestris* L.) it is the dominant species in the forests of Sumy Oblast due to its rapid growth and resistance to cold. Among the leading forest-forming regions is the silver birch (*Betula pendula* Roth.), while the northern red oak (*Quercus rubra* L.) is one of the most common non-native species.

Global climate changes can significantly affect the state of forest-forming species, which will lead to a decrease in the productivity of forest ecosystems, and changes in species composition and adaptation mechanisms (Yanitskyi, 2024). Therefore, the analysis of these aspects is important for developing strategies for forest management and biodiversity conservation. The purpose of the study was to analyse physiological and morphological changes in the most common (autochthonous and allochthonous) tree species of the forest ecosystem under the influence of climate changes, to investigated the adaptive mechanisms that these species use to overcome stressful climatic conditions. The main objectives of this study were:

- to consider the main biological properties of tree species in forest ecosystems of Ukraine and their response to environmental changes, in particular in a changing climate;
- to assess possible changes in the species composition, productivity and sustainability of forest ecosystems in Ukraine in the coming years in the context of global warming;
- to analyse existing forest management strategies, identify their gaps, and propose effective solutions to improve the viability of forest ecosystems.

Materials and Methods

In this paper, a comprehensive methodology involving both field and laboratory studies was used to analyse the relationship between climate change and adaptive responses of tree species. Key woodlands on the territory of forest-steppe Ukraine were selected as the research area, in particular, in Poltava, Sumy, and part of Chernihiv oblasts, where the main tree species to be studied (Scots pine, northern red oak, and silver birch) were represented. In general, the study covered the period 2021-2023 and the spring, summer, and autumn seasons. The final generalisation of the data was carried out based on the results of research in 2023.

During field monitoring, systematic monitoring of tree species during the growing season was carried out, in particular, calculating the height, trunk diameter, and general health of plants. Phenological observations were carried out aimed at studying the timing of flowering, vegetation, and leaf fall. A laser rangefinder (Leica LRF 1600, Switzerland) was used to measure the height of trees. Alternatively, telescopic altimeters were used to manually measure the height of trees, which allows for obtaining height data at different levels. A calper (Mitutoyo CD-6'CS, Japan) and a specialised diameter (Forestry Suppliers tree Diameter Tape, USA) were used to accurately measure the trunk diameter at breast height. Soil humidity and temperature sensors were used to assess environmental conditions that affect plant health. Field monitoring was carried out during the spring and summer seasons, when plants were actively growing.

Laboratory tests were also a significant part of the study. Samples of the leaves and bark of tree species were selected for further analysis for physiological characteristics such as chlorophyll content, photosynthetic activity levels, and resistance to mechanical damage. Leaf samples were processed in a laboratory to determine the chlorophyll content using a spectrophotometer (Thermo Scientific NanoDrop 2000, USA), which helped to obtain accurate data on the concentration of chlorophyll A and B in leaf tissue. The chlorophyll fluorescence method was used to analyse the level of photosynthetic activity, which included measuring the parameters of photosynthetic activity and quantum yields of photosynthetic reactions.

For the analysis of climate data, meteorological data obtained from local weather stations were used to assess changes in temperature, precipitation, and the frequency of extreme weather conditions between 1990 and 2024. Statistical methods have been applied to process and analyse the collected data, including correlation analysis, importance of variables, and multivariate analysis, to determine the relationship between climate factors and the biological characteristics of trees. Due to the analysis of variance (AOVA), the growth rates of trees at different temperatures and humidity levels were compared to determine the optimal conditions for their development. The Fischer criterion (F-test) helped to determine whether the difference in tree growth is significant under the influence of different climatic conditions. The Mann-Whitney U-test was used to study the effect of different precipitation levels on the survival of tree species in extreme droughts.

To calculate biological indicators, the authors used instructions on methods of biological and agrochemical studies of plants and soils. Chlorophyll fluorometry was used to measure the efficiency of photosynthetic processes in the most common woody species of forest ecosystems in the Poltava, Sumy, and Chernihiv oblasts – Scots pine (*Pinus sylvestris*), northern red oak (*Quercus rubra*), and silver birch (*Betula pendula*). The study was conducted in the summer and autumn periods to assess the resistance of these species to climate change, in particular, rising temperatures and changes in humidity. The study was conducted using a portable PAM-2500 (Pulse Amplitude Modulation) fluorimeter, which allows measuring the rate of induced chlorophyll fluorescence and evaluating the functioning of photosystem II (FSII). The main parameters that were measured were:

1. Fv/Fm – maximum possible quantum output ratio of FSII photochemistry in the dark.
2. Y(II) – actual quantum yield of FSII during light adaptation.
3. NPQ – non-photochemical quenching, showing the level of plant protective responses to stress.

The key equation for calculating the quantum yield of photosystem II was (1):

$$Y(II) = \frac{F'_m - F_s}{F'_m}, \quad (1)$$

where F'_m – maximum fluorescence under light adaptation; F_s – fluorescence in a stationary state.

As part of a study on the impact of climate change on Scots pine (*Pinus sylvestris*), northern red oak (*Quercus rubra*, and silver birch (*Betula pendula*) were air temperature and humidity monitoring throughout the growing season. These indicators were crucial for assessing stressful conditions affecting the physiological state of plants and for predicting future changes in forest ecosystems. Monitoring was carried out using two types of devices. HOBO U23 Pro v2 – air temperature and humidity recorder that allows obtaining accurate data in real time. TFA Dostmann manual thermohygrometer was used for periodic checks and verification of the received data. Monitoring was carried out for six months from April to September, when environmental conditions most significantly affect the vegetation processes of tree species. Significant fluctuations in air temperature and humidity were recorded. To assess the effect of temperature and humidity on plant physiological processes, the plant moisture availability index (MAI) was used, which was calculated using the equation (2):

$$MAI = \frac{P}{T}, \quad (2)$$

where P – average humidity for the period; T – average temperature for the period.

To calculate the biomass of trees, an equation was used that considers the parameters of height and diameter at breast height (DBH) (3):

$$M = a \times DBH^b, \quad (3)$$

where M – plant biomass (in kg); DBH – trunk diameter at breast height (usually at a height of 1.3 m from the ground, in cm); a and b – species-specific constants that were selected depending on the type of tree or region. All the information received was collected, systematised, and analysed to form generalisations that can provide recommendations for forest management in the context of global climate change and biodiversity conservation.

The analysis of international and national legislation was carried out using the comparative legal method by contrasting international agreements, such as Convention on International Trade in Endangered Species of Wild Fauna and Flora (1973), Convention on Biological Diversity (1992), United Nations Framework Convention on Climate Change (1992) and Fourth National Climate Assessment (2018), with national legislation in the field of forest protection, in particular the Law of Ukraine No. 1264-XII "On Environmental Protection" (1991) and the Forest Code of Ukraine (1994). This helped to identify the effectiveness of legal regulation in various jurisdictions and assess the compliance of national norms with international standards in the context of forest resource protection and sustainable management.

In the course of conducting this study, all the ethical standards specified in the above-mentioned legislative acts were observed. All research practices related to the collection of data on vegetation and trees were carried out in accordance with the principles of sustainable use of natural resources and protection of biodiversity. This ensures a responsible attitude to the environment and supports the ecological sustainability of forest ecosystems.

Results

Studies of adaptive mechanisms and physiological and morphological changes in woody species such as Scots pine, northern red oak, and silver birch under the influence of climate change reflect diverse responses to stressful conditions. The study, which concerned changes in the intensity of photosynthesis in tree species under the influence of climate change, was conducted during the spring and summer seasons. It is this period that is critical for the growth and active development of trees, since then photosynthetic activity is the highest, and the response of plants to stress factors (rising temperature, falling humidity) can be most noticeable (Stojko, 2011). For Scots pine: the intensity of photosynthesis decreased by 15-20% with an increase in temperature by 2-3°C. Northern red oak showed a smaller decrease in photosynthesis (by 10-12%), as its leaves have better resistance to overheating. Silver birch was more vulnerable, losing up to 25% of its photosynthetic activity at similar temperature increases. The above-mentioned studies of photosynthetic intensity were conducted in the forests of Poltava (Table 1), Sumy (Table 2), and Chernihiv (Table 3) oblasts, in particular, in oak-pine forests and oak-broad-leaved forest communities. The forests of this region, located on the border of the forest-steppe zone of Ukraine, are characterised by a significant variety of tree species, which provides favourable conditions for studying the impact of climate change on photosynthetic processes and adaptive mechanisms. Due to the diverse types of forest in the Poltava Oblast, the results of these studies allow assessing how different environmental conditions affect the physiological responses of tree species under the influence of stressful climate factors caused by climate change.

Table 1. Indicators of photosynthetic intensity of the main tree species of the Poltava Oblast

Plant type	Temperature rise	Spring period (change in photosynthetic intensity)	Summer period (change in photosynthetic intensity)
Scots pine	+1°C	-12%	-15%
Scots pine	+2-3°C	-15%	-20%
Northern red oak	+1°C	-8%	-10%
Northern red oak	+2-3°C	-10%	-12%
Silver birch	+1°C	-15%	-20%

Source: compiled by the authors

Table 2. Indicators of photosynthetic intensity of the main tree species of the Sumy Oblast

Plant type	Temperature rise	Spring period (change in photosynthetic intensity)	Summer period (change in photosynthetic intensity)
Scots pine	+1°C	-11%	-19%
Scots pine	+2-3°C	-15%	-24%
Northern red oak	+1°C	-7%	-10%
Northern red oak	+2-3°C	-9%	-14%
Silver birch	+1°C	-13%	-22%

Source: compiled by the authors

Table 3. Indicators of photosynthetic intensity of the main tree species of the Chernihiv Oblast

Plant type	Temperature rise	Spring period (change in photosynthetic intensity)	Summer period (change in photosynthetic intensity)
Scots pine	+1°C	-9%	-17%
Scots pine	+2-3°C	-12%	-20%
Northern red oak	+1°C	-5%	-8%
Northern red oak	+2-3°C	-7%	-10%
Silver birch	+1°C	-10%	-28%

Source: compiled by the authors

Scots pine in Sumy and Chernihiv oblasts also experienced a decrease in photosynthetic activity in the summer, which indicates its sensitivity to temperature increases. Despite this, it showed certain adaptive mechanisms that allowed it to partially compensate for the decline in photosynthesis. Northern red oak has demonstrated good resistance to temperature changes due to its powerful root system and ability to effectively regulate the water balance, which reduces the negative impact of high temperatures. Compared to other species, silver birch was the most vulnerable to climate change, especially during the summer heat, which led to a significant decrease in the intensity of photosynthesis. These results highlight how different tree species respond to rising temperatures in different areas of the forest-steppe zone, which can serve as a basis for further research and development of adaptation strategies (Shvydenko *et al.*, 2014; Oliynyk & Viter, 2021).

In comparison with the climate norm of 1961-1990, the forecast for 2029-2034 for the intensity of photosynthesis in the most common tree species in Ukraine indicates significant changes in physiological processes caused by climate change, in particular, global warming (Climate Change 2021..., 2021). According to the climatic norm, average annual temperatures were significantly lower, which limited the growing season. In the warming conditions, the growing season is expected to lengthen, especially in comparison with the norm, which will contribute to an increase in photosynthesis in the transition seasons (spring and autumn). For example, in 1961-1990, the photosynthetic activity of pine trees decreased with the onset of autumn cold weather, and now this process lasts longer due to the later arrival of cold weather (Moroz, 2024). The climatic norm assumed a more even distribution of precipitation, which maintained a stable water balance of plants. Current forecasts show that summer periods of drought, which were previously less common, will increase significantly. This will lead to a decrease in photosynthesis in species that are sensitive to water scarcity, such as silver birch, which showed a more stable level of photosynthesis under normal climatic conditions (Shevchenko *et al.*, 2014). The increased concentration of carbon dioxide in the atmosphere, which has increased in the last decade, will contribute to increased photosynthesis in species such as northern red oak in the initial stages of adaptation. However, if current global warming trends continue, this positive effect will be offset by other stressors (Ivanova *et al.*, 2021). According to the norms of 1961-1990, the species demonstrated a stable habitat. Now, due to rising temperatures, ranges are predicted to shift to the north, which will have consequences for photosynthesis and overall forest productivity. For example, Scots pine may begin to disappear from the southern regions of Ukraine, which was not observed during the climatic norm. Thus, compared to the period 1961-1990, global warming and climate change caused both positive and negative changes in the intensity of photosynthesis.

Tables 4-6 show the average values of key indicators of the level of protective reactions of tree species that were studied as part of the experiment. These indicators include: the maximum quantum efficiency coefficient of photosystem II, which allows assessing the level of stress in plants; the quantum yield of photosystem II, which shows the efficiency of photosynthetic processes; and the photoprotection indicator, which characterises the ability of plants to dissipate excess light energy to avoid damage. Based on the results of measuring the efficiency of photosynthetic processes in the most common tree species, the following average values were obtained for different tree species.

Table 4. Average values of indicators that reflect the level of protective reactions of trees in the forests of the Poltava Oblast

Tree type	Fv/Fm	Y(II)	NPQ
Scots pine	0.78	0.35	2.1
Northern red oak	0.81	0.4	1.9
Silver birch	0.75	0.32	2.4

Source: compiled by the authors

Table 5. Average values of indicators that reflect the level of protective reactions of trees in the forests of the Sumy Oblast

Tree type	Fv/Fm	Y(II)	NPQ
Scots pine	0.76	0.34	2.2
Northern red oak	0.8	0.42	2
Silver birch	0.73	0.3	2.5

Source: compiled by the authors

Table 6. Average values of indicators that reflect the level of protective reactions of trees in the forests of the Chernihiv Oblast

Tree type	Fv/Fm	Y(II)	NPQ
Scots pine	0.77	0.36	2.3
Northern red oak	0.82	0.43	1.8
Silver birch	0.72	0.28	2.6

Source: compiled by the authors

Scots pine in the forests of the Poltava Oblast showed an average Fv/Fm value of 0.78, which indicates minor photochemical disturbances, but an increased NPQ value (2.1) indicates activation of protective mechanisms in response to stressful conditions, in particular drought. Northern red oak showed the highest values of Fv/Fm (0.81) and Y(II) (0.4), which indicates a more efficient photosynthetic apparatus, but a lower level of NPQ (1.9), which may mean less stress resistance compared to pine. Silver birch showed the highest level of NPQ (2.4), indicating an increased stress response to exposure to high temperatures and low humidity, which are characteristic of climate change.

In the Sumy Oblast, Scots pine showed an average FV/Fm value of 0.76, which indicates minor photochemical disturbances, but an increased NPQ value (2.2) indicates activation of protective mechanisms under stress, in particular, drought. Northern red oak in the Sumy Oblast showed higher indicators of Y(II) (0.42), suggesting more efficient operation of the photosynthetic apparatus, but with NPQ (2), which indicates moderate stress resistance compared to pine. Silver birch shows the highest level of NPQ (2.5), which indicates an increased stress response to exposure to high temperatures and low humidity.

In the Chernihiv Oblast, Scots pine also showed satisfactory FV/Fm values (0.77), with NPQ (2.3) indicating its ability to adapt to stressful conditions. Northern red oak in the Chernihiv Oblast showed the highest values of Fv/Fm (0.82) and Y(II) (0.43), which indicates a high efficiency of photosynthesis, but with a lower NPQ (1.8), which may indicate lower stress resistance. Silver birch in the Chernihiv

Oblast also has a high level of NPQ (2.6), indicating strong stress reactions.

The quantum yield FSII under normal conditions should be approximately 0.83, but due to climate change, slightly reduced values for all species were observed, which indicates the influence of stressors (Murchie & Lawson, 2013). Based on these trends, photochemical efficiency indicators are expected to decrease further in all the studied species in the period 2029-2034, if climatic conditions (rising temperatures and decreasing precipitation) remain at the same level. This can lead to a gradual decrease in the overall productivity of these forests and, consequently, their ability to recover sustainably.

Monitoring climate conditions such as temperature and humidity was an important part of the study to assess stressors affecting the condition of trees and their biological properties (Lindsey & Dahlman, 2020). Based on the data obtained, significant fluctuations in temperature and humidity were recorded during this time, which allowed assessing stressful conditions for forest ecosystems. The average values of temperature and humidity at different stages of the growing season were as follows (Figs. 1 and 2).

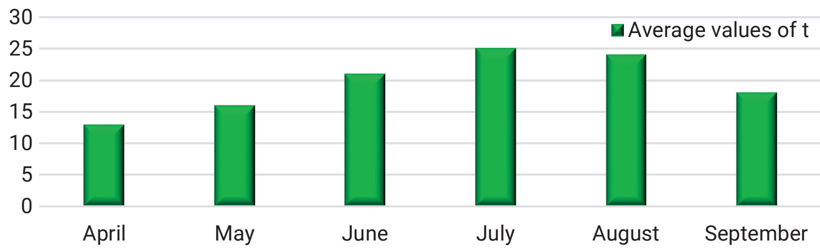

Figure 1. Average temperature values for the study months in three regions
Source: compiled by the authors

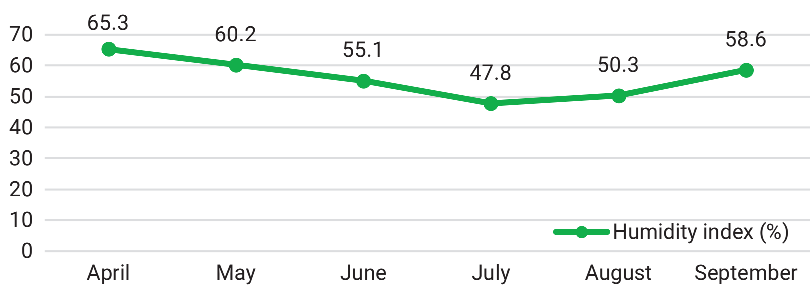

Figure 2. Average air humidity values by study month in the three regions
Source: compiled by the authors

These data are summarised based on the results of studies conducted in the Poltava, Sumy, and Chernihiv regions, which reflects general trends in the impact of climate changes on the physiological processes of tree species in the forest-steppe zone of Ukraine. The MAI score helped assess stress levels for plants at different stages of the growing season. For example, in June in the Poltava Oblast:

$$\text{MAI June} = \frac{55.1}{20.8} = 2.65,$$

$$\text{MAI July} = \frac{47.8}{25.3} = 1.89.$$

Sumy Oblast:

$$\text{MAI June} = \frac{53.2}{19.5} = 2.73,$$

$$\text{MAI July} = \frac{45}{24.5} = 1.84.$$

Chernihiv Oblast:

$$\text{MAI June} = \frac{54}{21} = 2.57,$$

$$\text{MAI July} = \frac{46.5}{23.8} = 1.95.$$

The low index in July indicated a critical level of water stress for pine and birch trees. The forecast for 2029-2034 shows a possible increase in temperature by another 1-2°C, which will lead to a further decrease in humidity, especially in July-August. This can cause severe water stress in tree species and a decrease in their viability. An increase in the frequency of droughts is a possible scenario, which is especially dangerous for silver birch and northern red oak.

It was important to analyse the growth rate of plants and their biomass indicators during the study. Scots pine has reduced its leaf area by 10% in drought conditions. Northern red oak lost up to 8% of the leaf area, but adapted faster to the changes. In silver birch, the leaf area decreased by 15%, which was also accompanied by a decrease in the amount of chlorophyll. Scots pine showed a 5-7% decrease in annual growth under stressful climatic conditions. Northern red oak reduced its growth rate by 4-6%, but due to its deep root system, it retained its productivity. Silver birch experienced the greatest decline – by 10-12%, especially in drought conditions.

Evaluation of the morphological characteristics of trees showed that pine trees have a thickening of the bark tissue by 10-15%, which increases resistance to drought. Northern red oak increased wood density by 5-7% in response to stress (Table 7). Silver birch exhibited less adaptive plasticity, showing a change only in the number of shoots formed (a decrease of 20%).

Table 7. Morphological characteristics of the main tree species in comparison with the climatic norm of 1961-1990, average values for three areas of research

Tree type	Parameter	Norm (1961-1990)	Current state	Deviation, %
Scots pine	Height of young trees (m/year)	0.6	0.55	-8.33
	Height of adult trees (m/year)	0.4	0.35	-12.5
	Diameter of young trees (cm/year)	1	0.9	-10
	Diameter of adult trees (cm/year)	0.6	0.55	-8.33
	Biomass of young trees (t/ha)	2.7	2.7	0
	Biomass of adult trees (t/ha)	4	4	0
	Needle length (cm)	7.5	6.9	-8
	Number of small roots (%)	10	12	+20
Northern red oak	Height of young trees (m/year)	0.5	0.45	-10
	Height of adult trees (m/year)	0.3	0.25	-16.67
	Diameter of young trees (cm/year)	0.8	0.7	-12.5
	Diameter of adult trees (cm/year)	0.5	0.4	-20
	Biomass of young trees (t/ha)	3.2	3.2	0
	Biomass of adult trees (t/ha)	5	5	0
	Leaf area (cm^2)	100	115	+15
	Root system depth (m)	2	2.36	+18

Table 7, Continued

Tree type	Parameter	Norm (1961-1990)	Current state	Deviation, %
Silver birch	Height of young trees (m/year)	0.7	0.65	-7.14
	Height of adult trees (m/year)	0.45	0.4	-11.11
	Diameter of young trees (cm/year)	1.2	1.1.	-8.33
	Diameter of adult trees (cm/year)	0.8	0.7	-12.5
	Biomass of young trees (t/ha)	3.8	3.8	0
	Biomass of adult trees (t/ha)	4.5	4.5	0
	Leaf thickness (mm)	1.5	1.35	-10
	Main root length (m)	1.5	1.32	-12

Source: developed by the authors based on O. Shevchenko & S. Snizhko (2019), and V.O. Balabukh (2013)

Tree biomass calculation indicators show the amount of organic mass accumulated in the wood, root system, leaves, and other parts of the plant. They are important for assessing the ecological role of forests, the ability of trees to accumulate carbon, and regulate the carbon cycle. For example, if for Scots pine the value of the constants $a = 0.05$ and $b = 2.5$, and the diameter of the tree at chest height is 25 cm, the equation will look like this:

$$M = 0.05 \times 25^{2.5} \approx 49.67 \text{ kg}.$$

These calculations are important for estimating carbon stocks in forest ecosystems and studying environmental changes under the influence of climate (Fig. 3).

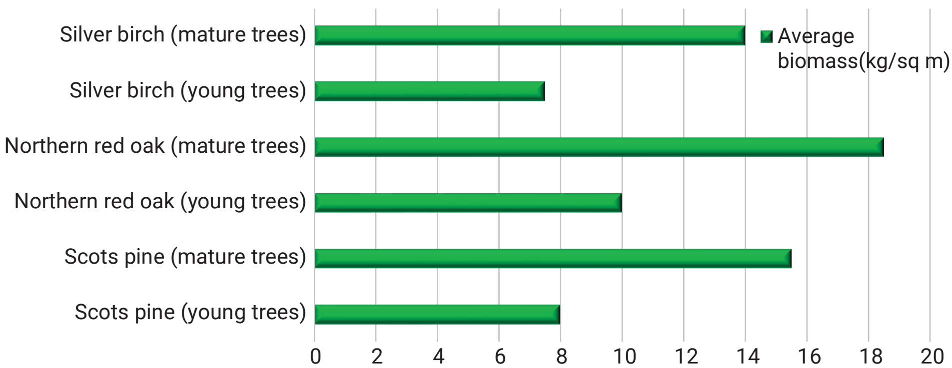

Figure 3. Indicators of biomass of tree species, average values for three study areas
Source: compiled by the authors

The data obtained in the study allow analysing and determining the main adaptive mechanisms of tree species of the forest ecosystem under study, which are important for their survival and function in the context of climate change. Scots pine adapts to dry conditions by reducing the leaf surface area (needles), which helps to reduce water evaporation. Needles often become thinner and have a smaller surface area. Pine has a deep root system that allows it to extract water from the lower layers of the soil during droughts. During the cold season, pine has the ability to synthesise antifreeze substances (for example, sugars), which protects cells from damage from low temperatures. Pine can recover from forest fires due to cones that open only at high temperatures, and sowing seeds in places cleared of burning materials. Northern red oak has the ability to adapt to changes in moisture due to its powerful and widely branched root system, which allows it to get water from different layers of the soil. Oak leaves can change their shape and size depending on environmental conditions. Under stressful conditions, the leaves may become smaller, which reduces water evaporation. Oaks have a long life cycle and can recover slowly, which helps them withstand prolonged climate change and environmental stresses. Oaks have a high ability to accumulate energy reserves in their roots and trunks, which allows them to withstand periods of stress. Silver birch has a high growth rate and the ability to quickly recover from damage, which allows it to successfully compete for resources in the face of rapid changes. Birch can grow in a variety of soil types, including poor and acidic soils, due to its symbiotic relationship with root fungi, which help it absorb the necessary elements. Trees of this species have phytochemicals that repel many pests and pathogens, which helps it to maintain its health even in conditions of environmental stress. Birch leaves can adapt to changes in light and moisture conditions, for example, by changing their shape and size to optimise photosynthetic activity.

All of these species have common adaptive mechanisms, such as changing the shape, size, and thickness of leaves, needles, or roots, storing energy as spare substances for use under stressful conditions, and being able to recover quickly from environmental stresses such as droughts or floods (Resolution of the..., 1995; Miniaylo *et al*., 2014).

These adaptation methods allow tree species to maintain their viability and functionality in changing climates, ensuring their resilience and longevity in forest ecosystems. The results of field work and experimental studies clearly demonstrate significant changes in the biological characteristics of tree species in the context of global climate change. Observations of growth rates, productivity, and morphological changes in Scots pine, northern red oak, and silver birch indicate clear deviations from the climatic norm of 1961-1990. Studies have clearly shown that existing climate changes have a significant impact on the biological characteristics of tree species in forest ecosystems. Observations of growth rates, productivity, and morphological changes confirm the need for urgent search and development of new forest management strategies. Given the identified trends, the task of creating adaptive management approaches that will ensure the effective conservation and sustainable use of forest resources in the context of global climate change is extremely urgent.

The state forest management strategy until 2035 in Ukraine can play a key role in ensuring the adaptation of forest ecosystems to global climate change (Order of the..., 2021). The strategy includes risk assessment for different forest zones, which will identify the most vulnerable regions, development of recommendations for changing reforestation and forestry practices that consider new climatic conditions, in particular, changes in the species composition of forests, development of programmes for the conservation of biodiversity, including for the support of rare and threatened species. The introduction of monitoring systems to track changes in biodiversity and conservation effectiveness is part of the strategy (Convention on International..., 1973; Solomakha *et al*., 2020).

Forests play a key role in combating climate change and promoting sustainable development because of their ability to absorb carbon, maintain biodiversity, and ensure the sustainable use of natural resources. Their conservation and restoration are important for regulating global climate processes, as forests act as huge reservoirs for carbon, absorbing up to 30% of greenhouse gas emissions caused by human activities (Hartmane *et al.*, 2024). Through photosynthesis, trees absorb carbon dioxide (CO_2) from the atmosphere, fixing it in its biomass, including trunks, roots and leaves. Conservation of existing forests and restoration of felled areas contribute to reducing CO_2 concentrations in the atmosphere, which is crucial for mitigating the effects of global warming. Young trees absorb carbon faster during active growth, and older forests store significant amounts of carbon in the soil and wood (Tykhonova *et al.*, 2024). Thus, the restoration of forest stands and sustainable management of existing forests allow both the capture of new carbon and the storage of previously accumulated carbon in soil systems. According to research, plantation forests have the potential to absorb carbon quickly, but it is older woodlands that contribute most to long-term carbon storage. This means that a strategy to combat climate change should combine both planting new trees and preserving old ecosystems that are carbon "warehouses". In the long run, forest conservation can help to stabilise the climate by balancing the carbon cycle and reducing greenhouse effects (Didukh *et al.*, 2024).

The use of forest resources in a circular economy makes them a key element of sustainable development. The circular economy involves the rational use of resources, waste reduction and maximising the efficiency of renewable natural resources such as wood. Forests are becoming important suppliers of biomass that can be used for the production of bioenergy, building materials, and even for the production of biodegradable materials that replace plastics. Forest-based bioeconomics promotes economic growth while reducing dependence on fossil energy sources (Mishenin & Oliynyk, 2010; Shtuk, 2022). Wood and other forest products are renewable resources that can be reused and recycled. For example, wood waste can be recycled to create biofuels or compost, which reduces carbon emissions and promotes cyclical use of resources. Forests also play an important role in supporting ecosystem services such as water conservation, preventing soil erosion, and providing habitat for many plant and animal species. The integration of forest resources into the circular economy allows not only to ensure the sustainable use of natural resources, but also to preserve ecosystem functions that are vital for ecological balance (Kirchherr *et al.*, 2017). However, the use of forests in bioeconomics requires a balanced approach, since excessive or uncontrolled use of wood can lead to ecosystem degradation. Modern technologies, such as remote sensing and geoinformation systems, contribute to more accurate monitoring of the state of forests, helping to identify negative trends in forest stands and implement timely measures for restoration and protection.

Discussion

The study of the impact of global climate change on the biological characteristics of tree species in forest ecosystems is of great importance not only for science, but also for practical aspects of forest management. The findings highlight important trends that may have long-term implications for biodiversity, ecosystem functioning, and climate change adaptation strategies. The study of the biological characteristics of trees has shown that an increase in temperature and changes in humidity regimes have a noticeable effect on the growth and productivity of tree species. For example, species that have adaptive mechanisms, such as increased root systems or reduced foliage, have been found to have a better chance of surviving in a changing climate.

The study, in particular, demonstrated that these adaptations not only contribute to the survival of individual species, but can also affect the overall structure of forest communities.

The data obtained can also serve as a basis for formulating evidence-based recommendations for managing forest resources in the face of climate change. This is consistent with the study by I. Buksha *et al*. (2023), who noted that some tree species show particular sensitivity to climate change, while others can adapt to new conditions. Such observations highlight the importance of monitoring tree species and their adaptation strategies. Experiments have shown that changes in temperature significantly affect photosynthetic processes in tree species, which, in turn, leads to changes in the structure of forests. Our results support this trend, as it was found that an increase in the average annual temperature leads to an increase in the intensity of photosynthesis in some species, such as Scots pine.

The Fourth National Climate Assessment (2018), as part of the US Climate Change study, highlighted the importance of adaptive strategies for maintaining ecosystem sustainability. The assessment focuses on the urgency of taking measures to minimise the effects of global warming. The analysis is consistent with the provisions of this report, as it also examines the impact of climate change on forest ecosystems and biodiversity, in particular, on the adaptation strategies of tree species in response to rising temperatures and changing humidity regimes. This study is part of an overall trend aimed at predicting and minimising the negative effects of climate change.

United Nations Framework Convention on Climate Change (1992) is an important international agreement aimed at reducing greenhouse gas emissions and stabilising the climate. It emphasises the need for adaptive measures to prevent the negative effects of climate change, including the conservation of natural ecosystems. The analysis of environmental processes carried out within the framework of this project is consistent with the goals of the convention, focusing on the study of the impact of climate change on forest ecosystems and the development of strategies for adapting tree species to changing environmental conditions. However, the results of this study also show that not all species respond equally to climate change. For example, in conditions of reduced humidity, a decrease in productivity was observed in silver birch, which may be conditioned by its high sensitivity to water deficiency. This is an important aspect, as it indicates potential risks for specific species that may be displaced by more resilient competitors in a changing climate.

The adaptive mechanisms of tree species in response to climate change are also worth analysing. As indicated by O. Shevchenko (2017) and Z.M. Budnik *et al*. (2023), some species are capable of changing morphological characteristics to ensure their survival. This includes changes in leaf size, shape, and depth of the root system. For example, in the present study, Scots pine showed a marked increase in the root system, which may indicate its ability to adapt to conditions of limited water supply.

V.S. Oliynyk & R.M. Viter (2021) focused on studying the impact of climate change on ecological processes in forest ecosystems. The researchers considered how rising temperatures and changing humidity patterns can affect the growth, productivity, and resilience of tree species. They also focused on the adaptive mechanisms that different species use to survive under stress, in particular, the study of morphological changes in root systems and leaf mass. The current study provides new data on specific morphological changes in Scots pine under elevated temperature conditions, such as a marked increase in the root system, indicating the adaptive mechanisms of this plant. Thus, the results of this study complement the conclusions of the above researchers, expanding the understanding of the adaptive responses of tree species at the local level.

Yu. Shtuk (2022) analysed climate change in Ukrainian cities, considering their impact on urban infrastructure and ecosystems, with a focus on forecasts for the end of the 21st century based on representative concentration pathways (RCP) scenarios. The researcher noted that changes in temperature and reduced water resources can seriously affect urban living conditions. The current study also includes forecasts of the impact of climate change on the biological characteristics of tree species in forest ecosystems. Although the above study focused on an urban context, this project offers predictions about how global climate change might affect specific plant species, highlighting the importance of analysing not only urban but also natural ecosystems in the face of climate change. This analogy demonstrates the need for an integrated approach to studying the impact of climate change on various aspects of the environment.

The results are important for understanding the impact of global climate change on tree species. Adaptive mechanisms such as root system changes and photosynthetic activity have been found to contribute to the survival of certain species under stress. This can affect the biodiversity and functioning of forest ecosystems. Knowledge of these adaptations is important for developing forest management strategies that will help to maintain ecological balance and maintain ecosystem resilience in the face of climate change. The conducted research opens up a number of areas for further study. Firstly, it is important to conduct long-term monitoring of tree species to better understand how climate change affects their growth and adaptation mechanisms. In particular, it will be of interest to study how different types of soils and landscapes affect the adaptation of species to changing conditions. Secondly, it is promising to study the impact of climate change on interactions between different species in forest ecosystems. This will help to understand how changes in one species can affect other species and the ecosystem as a whole.

The adaptive mechanisms of tree species in the context of climate change should continue to be studied to develop effective forest management strategies. This includes integrating research results into natural resource management policies, which are critical to ensuring the sustainable development of forest ecosystems. The results indicate the need to develop new forest management models that consider the specific adaptive mechanisms of tree species. Understanding how climate change affects morphological and functional characteristics can serve as a basis for shaping environmental policy. This knowledge is important not only for the scientific community, but also for practical management decisions. In particular, it is worth focusing on preserving biodiversity and maintaining ecosystem stability. In light of the findings, further research should focus on the long-term effects of climate change that may affect the future of forest ecosystems.

Conclusions

The study, conducted to analyse physiological and morphological changes in Scots pine, northern red oak, and silver birch under the influence of climate change, revealed significant adaptive mechanisms that these species use to overcome stressful conditions. In particular, it was found that an increase in average temperature and changes in precipitation regimes negatively affect the growth and development of these trees. Findings show that when the temperature increased by +1°C, the intensity of photosynthesis in Scots pine decreased by 12-15% in the Poltava Oblast, while in the Sumy and Chernihiv Oblasts the drop reached 11-19% and 9-17%, respectively. The greatest losses of photosynthetic activity were recorded in the summer, when the temperature increased by

2-3°C, especially vulnerable was the silver birch, which showed a decrease in the intensity of photosynthesis up to 28% in the Chernihiv Oblast.

Analysis of the level of protective reactions of tree species confirmed the presence of various adaptive mechanisms. For example, the average NPQ values for Scots pine in the Poltava Oblast reached 2.1, which indicates the activation of photoprotective mechanisms under stress. In Sumy and Chernihiv oblasts, NPQs for pine trees were higher (2.2 and 2.3, respectively), which indicates an increased response to stressful conditions. Northern red oak showed more stable FV/Fm and Y(II) scores, indicating better adaptation to climate change in all regions.

According to MAI calculations, in June in the Poltava Oblast, this figure was 2.65, and in July it decreased to 1.89, which indicates a critical level of water stress for pine and birch. Sumy Oblast showed similar trends: MAI in June was 2.73, and in July – 1.84. Chernihiv Oblast had the highest MAI in June (2.57) and the lowest level in July (1.95), which indicates the influence of high temperatures on the water supply of plants.

The data obtained indicate possible changes in the species composition of Ukrainian forests, which may lead to a decrease in their productivity and overall ecological sustainability. The identified adaptations include changes in the morphology of leaves and root systems, which allows plants to optimise water and nutrient supply under stress. Important recommendations for further research are the development of methods for monitoring the impact of climate change on forest ecosystems, which may include analysis of phytodiversity and environmental regimes. This will better assess the vulnerability of forests to climate change and provide more effective conservation strategies.

The conditions of this study are that it was conducted for a limited period, which may not reflect long-term trends in changes in vegetation and their adaptation to climate. The results may be specific to the regions under study and cannot be directly generalised to other climatic or geographical areas. Consideration of these aspects in subsequent research will help to better understand the processes of adaptation of forest species to climate change and identify more effective approaches for their conservation in the face of global warming.

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Conflict of Interest

None.

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Вплив глобальних змін клімату на біологічні характеристики деревних видів у лісових екосистемах

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Анотація. Мета даного дослідження – аналіз фізіологічних і морфологічних змін у найпоширеніших деревних видів лісової екосистеми під впливом кліматичних змін, а також дослідження адаптаційних механізмів, які ці види використовують для подолання стресових погодних умов. У дослідженні розглядається вплив глобальних змін клімату на біологічні характеристики сосни звичайної, дуба червоного і берези повислої. Зокрема, аналізуються адаптаційні механізми дерев, які дозволяють їм виживати та пристосовуватись до умов, що змінюються. Вивчено вплив підвищення середньої температури, зміни режимів опадів та екстремальних погодних явищ на ріст, розвиток і розмноження деревних рослин. Використані методи польового моніторингу та лабораторні експерименти для збору даних про фізіологічні та морфологічні зміни, що відбуваються з видовими групами дерев під впливом кліматичного тиску. Результати дослідження показують, що глобальні зміни клімату можуть призвести до значних трансформацій у видовому складі лісів, їхньої продуктивності та загальної екологічної стійкості. Отримані дані підкреслюють необхідність адаптаційних стратегій для управління лісовими ресурсами та збереження біорізноманіття в умовах глобальних кліматичних змін. Дослідження також розглядає інструкції для практичних дій, спрямованих на пом'якшення негативних наслідків зміни клімату на лісові екосистеми. Оцінено вразливості лісів України у зв'язку зі зміною клімату у XXI столітті порівняно із кліматичною нормою (1961-1990 рр.). Надані рекомендації щодо оцінювання впливу кліматичних змін на ліси, аналізу фіторізноманіття та екологічних режимів за даними моніторингу лісів у контексті нормативно-правових актів України, зокрема, Державної стратегії управління лісами до 2035 року та рекомендацій Державного лісового кадастру України. Результати дослідження можуть бути використані для розробки стратегій управління лісовими ресурсами, впровадження адаптаційних заходів у лісовому господарстві, а також для моніторингу стану лісових екосистем і прогнозування їхньої стійкості до кліматичних змін у рамках національних екологічних програм

Ключові слова: кліматичний тиск; біорізноманіття; фізіологічні зміни; продуктивність лісів; моніторинг екосистем; адаптаційні механізми

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Water-physical properties of gray forest soils and their root settlement in areas of anthropogenic trampling

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Abstract. The aim of the study was to monitor the impact of anthropogenic trampling of gray forest soil on their content of water, air, solid particles and the mass of fine and coarse roots. The contents of mass of solid particles, volume of air, water and its permeability were determined according to generally accepted methods using of measuring cylinders. Soil roots colonization was measured by the method of "monoliths". It was found out that under the impact of anthropogenic trampling, water reserves in the upper 50-centimeter layer of soils were 1.6-5.3% higher than under matured oak-hornbeam stand without visible signs of degradation, and the soil water saturation coefficient during the research was lower (0.21-0.43%) than the optimal values (0.80%). At the same time, the greatest destruction changes were experienced by the researched physical indicators in a humus horizon of gray forest soils. An increase of solid particles (by 14.1-22.8%), decrease of air pores (by 32.0-44.3%) and the mass of fine roots of trees (by 84.6-91.2%) in the 10-cm soil layer were recorded. It is found that in the event of cessation of trampling of the path surface, the natural recovery of degraded physical indicators in compacted soils happens most intensively in the 5-centimeter horizon. At the same time the changes in the decrease of solid particles (by 9.9%), an increase of pores (by 39.1%) and fine roots of trees (by 330.0%) were observed over a 15-year period. The obtained quantitative and relative indicators of the content in anthropogenically compacted soils of solid particles, water and air explain the features of its settlement by roots of vegetation, and also indicate the applied significance of the results presented in the study

Keywords: soil compaction; permeability; park plantings; aboveground cover; soil colonisation by roots

Introduction

Anthropogenic trampling of the soil surface is most significantly manifested within urban landscapes especially in green plantations, where the negative consequences of trampling are manifested due to the deterioration of their ecological functions, as well as in soil dehumification and increased manifestation of external signs of erosion processes and a decrease in the number, or even the complete disappearance of certain species from plant communities. Usually, soil compaction causes functional changes in edaphotopes, and also affects the quantitative and relative indicators related to the species composition of plant cover and affect the microclimatic indicators of the surrounding areas.

Studies on this topic have been conducted in various regions, highlighting the consequences of human activities. N. Nir *et al.* (2022) analysed the long-term paedogenic and geomorphological effects of human trampling. Their findings indicate that persistent recreational impacts lead to soil compaction, changes in water infiltration, and erosion, with far-reaching consequences for ecosystems. Researches D. Selesa & A. Cerda (2020) presented a comprehensive review of soil erosion on mountain trails caused by recreational activities. The researchers emphasised the role of soil hydro-physical properties in degradation processes, particularly the reduction in moisture retention and infiltration capacity under human pressure. Numerous studies on trampling of recreational areas have confirmed the reduction in the number of woody and herbaceous species, their cover density, reduction in increment of wood and suppression of growth (Atic *et al*. 2009; Li *et al*., 2020).

Scientists M. Kissling *et al.* (2009) investigated short- and long-term effects of trampling in suburban beech forests. They observed that trampling causes soil compaction, reduces organic matter content, and disrupts microbial processes. These changes impair soil fertility and natural nutrient cycling. Ya. Henyk *et* *al.* (2014) examined changes in the physicochemical properties of soils in urban parklands and woodlands in Ukraine under recreational load. Their findings revealed decreased porosity, reduced water permeability, and increased soil compaction due to trampling, which limits root growth.

The beginning of digressive changes in phytocenoses that occur during trampling is visually determined by the degree of degradation of vegetation cover. With permissible soil compaction, the result of trampling is clearly visible within the paths, playgrounds, recreational objects, which can be evaluated by the degree of recreational digression and degradation of grass cover (Lenevych *et al*. 2021; Kalahroudi *et al.,* 2023).

The problems associated with anthropogenic soil trampling began to take on clear outlines from the second half of the 20th century and have now become the subject of research by both researches and scientists in various fields of knowledge, which relate to the ecology of plantations of natural and artificial origin. During this long period, it was found that soil compaction causes changes in the structure of the soil, as well as their physical properties. This is manifested in changes in soil porosity, deterioration of their temperature regime and water-physical properties. These changes negatively affect the nutrition regime of woody and herbaceous plants. In particular, O. Ryzhov *et al.* (2014) studied that for sandy soils, the optimal density (volumetric mass) is within 1.20-1.45 g/m^3. If the soil compaction is 1.20 g/m^3 and less – the soil is not retained moisture. The plants suffer greatly from its lack. It negatively affects the growth and functioning of the root systems of woody plants.

The mentioned information on water-physical properties refers to different types of soils, and therefore the clarification of the impact of anthropogenic on their forest vegetation properties should be carried out with the involvement of the same type of research methods with subsequent detailing and clarification of the obtained results.

The main aim of the study was to find quantitative and relative indices that reflect the impact of anthropogenic trampling on the water content, solid particles and cracks in gray forest soils and their population by roots.

Materials and Methods

The research was conducted in compliance with the ethical standards set forth in the Convention on Biological Diversity (1992). The research object was a path located in the southern part of Holosiivo Park of Culture and Recreation named after Maksym Rylskyi, in the Kyiv city. The height of exceedance, in the range from the lower dam of the third Horikhuvatskyi pond (coordinates: 50°23´26´´ N and 30°30´88´´ E) to the stop of bus 212 (coordinates 50°23´46´´ N and 30°30´24´´ E), reaches 50 m and the objects of this study are at an altitude of 155-160 m above sea level. The current contours of the path were formed more than 30 years ago, as a result of annual trampling of the soil surface by residents of the areas adjacent to the park, vacationers and students studying at the National University of Life and Environmental Sciences of Ukraine (Brovko *et al.*, 2023).

The formation of the research object occurred in the summer of 2004, when a *Tilia cordata* Mill. tree blocked a hiking trail due to a windstorm (Nesterov, 2007). The field research was carried out in August 2019 and the desk work – in 2020-2021. The study was conducted within the path, which was located in 90-year-old oak-hornbeam stand in the park space of the Kyiv city, in order to estimate the impact of anthropogenic pressure on the changes of water-physical indicators in the gray forest soils. The path was trampled under the plantation formed of deciduous woody plants, among which, at the time of the research, five species dominated, and their share in the composition of the tree layer was *Quercus robur* L., *Betula pendula* Roth., *Carpinus betulus* L., *Tilia cordata* Mill., *Acer platanoides* L., which indicates its derivative origin, because it grows in the area belonging to hornbeam groves (Holosiivskyi National Nature Park, n.d.).

The diameters of the trees were quite variable and ranged from 20 cm (hornbeam, sapling origin) to 50 cm (birch, seed origin), and the height of the trees that formed the main layer of the plantation reached from 22 up to 27 m, which in terms of productivity corresponds to higher classes of productivity. Intermediate values of biometric indicators were observed in the rest of the trees present on the site. The canopy closure, during the vegetation period of the trees, reaches more than 0.9 units. That prevents the penetration of sun's rays under the canopy on hot summer days, providing the much-desired coolness for park visitors.

Studies conducted by Y. Nesterov (2007) in this area of Holosiivskyi Park showed the drying out of birch and its loss from the stand. It is also worth noting that over the past 15 years in this phytocenosis there has been a drying up of the birch (Fig. 1a).

a *b* *c*

Figure 1. Dead trunks of birch within the path area
Note: a) trunks that have fallen from the composition of the stand; b) fallen trunk near the path; c) trunk that fell into an area without visible signs of trampling the soil
Source: authors' photo

Usually, the root systems of birches die, and therefore their trunks fall out of the ground, both near anthropogenically trampled areas (Fig. 1b), and in areas where the soil surface does not have visible signs of trampling of grass cover (Fig. 1c), which testifies to the complexity of this phenomenon, which is apparently connected not only with the compaction of the soil layer, but also with the birch reaching the age of natural ripeness.

Tree trunks with dead roots, after being blown down by the wind, not only clutter up the territory of the park and worsen the aesthetic appeal of the area, but also become inhabited by different pathogens and wood-destroying fungi, in particular *Fomitopsis pinicola* and *Fomes fomentarius*, which significantly accelerate the natural decomposition of dead wood.

Soils within the studied part of the park, by the nature of changes in the structure of the soil profile, belonged to partially transformed upper horizons with a preserved natural profile and according to classification (Pozniak & Teleguz, 2021) were identified as anthropogenic-natural subtypes that belong to types of natural soils. According to Y. Nesterov (2007) these were gray forest soils. That type of soil formed on loess loams. They were characterised by a humus horizon 20-22 cm thick, an insignificant humus content (up to 2%) and unsatisfactory aeration of the upper layers of the soil, which against the background of the available acidity (saline pH = 4.3-4.5) negatively affected the course of microbiological processes and as a result, it was manifested by a weak mobilisation of mobile forms of nitrogen.

The study of the impact of soil compaction on the content of water resources in them and on their settlement by roots was carried out within three locations of this plantation. The first (1), without visible signs of anthropogenic trampling of the grass topsoil, was located at coordinates 50°23´36´´ N and 30°29´50´´ E and served as a "control". The second, a path that had been used as intended for over three decades (2). The site where samples were taken for research was located at the coordinates 50°23´20´´ N and 30°29´49´´ E. There was no vegetation cover on the surface of the path (Fig. 1). The third part of the path, which had not been used for its functional purpose for the past 15 years (3), due to the fact that dead trunks of *Tilia cordata* Mill fell across the path in 2007 year (Nesterov 2007) and *Betula pendula* Roth., which made it impossible for park visitors to pass comfortably along this part of the path. The coordinates of the sampling site for the study were 50°23´29´´ N and 30°29´52´´ E. At the time of the survey, this part of the path was littered with the remains of a dead birch trunk that fell in 2014, and its natural overgrowth, occurred due to self-sowing of *Ulmus scabra* L., (there were up to 5 pc./m^2). The height of the seedlings reached up to 2.2 m, and the diameters of their trunks at the root neck – up to 2.6 cm. It was also worth noting that lower biometric indicators of the trunks were observed in the seedlings that grew in the central part of the path.

Water and physical properties of studied soils were determined in 3-5 repetitions. Test samples were selected in every 5 cm in the depth to 50 cm. In particular, soil moisture in its natural state was determined according to formula (1):

$$W_M = \frac{W_V}{M_{CS}} \cdot 100, \qquad (1)$$

where: W_M – soil moisture in its natural state, in weight %; W_V – the mass of water that evaporated from the weight of the soil during its drying, g; M_{CS} – weight of the soil in a completely dry state, g.

The compaction of the soil structure in a completely dry state was determined by formula (2):

$$D_S = \frac{E \cdot 100}{V \cdot (100 + W_M)}, \qquad (2)$$

where: D_S – compaction of the soil in a completely dry state, g/cm^3; E – mass of wet soil in the cylinder, without the mass of the cylinder, g; V – the volume of the cylinder used for soil sample selection, cm^3; W_M – water content in the soil, in its natural state, in weight %.

The calculation of the water content in the upper 50-centimeter soil layer was carried out according to formula (3):

$$B = a \cdot d_v \cdot h, \qquad (3)$$

where: B – water content, m^3/ha; a – moisture content of the soil layer, in weight %; d_v – compaction of the soil layer, g/cm^3; h – soil layer in which the water content was determined, cm.

The water permeability of the upper 10-centimeter layer of soil was determined by alternating water pressure to wet the soil outside the recording site, the cylinder that limited the contours of the site was placed in the middle of a larger cylinder (52.78 cm^2) filled with water. During the experiment, the same water level was maintained in both cylinders. Calculation of water permeability of the soil was carried out according to formula (4):

$$K = \frac{G}{S \cdot T} \cdot K_{10}, \qquad (4)$$

where: K – water permeability of the soil, ml/h; G – the amount of water supplied to the accounting site, 1000 ml; S – the area of the accounting site, 26.86 cm^2; T – duration of water absorption, h; K_{10} – coefficient of reduction to a temperature of 10°C (1.0075).

The assessment of water permeability of the soil, within the studied locations, was carried out according to the Kaczyński scale. The scale consists of 6 positions, namely (in mm/hour): failed – >1000; excessively high – 1000-500; the best – 500-100; good – 100-70; satisfactory – 70-30; unsatisfactory - <30.

To determine the content of solid particles, water, air, cracks and the coefficient of their saturation with water, cylinders with a volume of 61.64-67.40 cm^3 were used. Soil in an undisturbed state was collected in cylinders in 5-fold repetition, weighed on the laboratory scales, the obtained results were recorded in the field journal. After that, the soil cylinders were saturated with water until the change in their mass stopped. Then, repeated weighing of cylinders with soil saturated with water was carried out. The obtained data and the mass of the soil at natural humidity were converted to completely dry soil according to formula (5):

$$N_{CS} = \frac{M_V \cdot 100}{V_C \cdot (100 + W_P)}, \quad (5)$$

where: M_{CS} – mass of soil in a completely dry state, in 100 cm^3, g; M_V – soil mass, in a cylinder at natural water content, g; V_S – cylinder volume, cm^3; W_P – water content in the soil under natural conditions of determination, %.

The content of the soil, in cylinders saturated with water, under natural humidity and in a completely dry state, was converted to its content in 100 cm^3, by dividing the mentioned indicators by the volume of the cylinders that contained the soil, and the obtained result was multiplied by 100 (cm^3).

The content in 100 cm^3 of solid particles (absolutely dry soil), water (the difference between the soil saturated with water and the absolute dry mass of the soil, identified as the content of cracks), air (water that displaced the air) was determined, in %, by formula (6):

$$X_P = \frac{M_P \cdot 100}{N_{NW}}, \quad (6)$$

where: X_P – content in 100 cm^3 of the soil of the studied components, in % by volume; M_R – content in 100 cm^3 of the studied component, g; M_{NW} – content in 100 cm^3 of soil completely saturated with water, g.

The coefficient of water saturation of cracks in the soil was determined by formula (7):

$$K_{NW} = \frac{N_W}{M_{PC}}, \quad (7)$$

where: K_{NW} – soil water saturation coefficient, under natural conditions, a dimensionless value; M_W – water content in 100 cm^3 of soil under natural conditions of determination, g; M_{PC} – water content that filled all the cracks in 100 cm^3 of soil, g.

The content of roots in the upper 50-centimeter soil layer at the studied locations was determined by the monolith method (Pozniak & Teleguz, 2021) in 5-fold repetition. Soil samples with roots were taken with a drill with a cross-sectional area of 55.39 cm^2 and a height of the working surface of 10 cm. The root mass content in the studied soil layer was determined according to the method described in the article F. Brovko *et al.* (2023).

The average values were calculated using Microsoft Excel and STATISTICA 8.0 programme packages (Paianok & Zadorozhnia, 2020). The significance of the difference between the means of obtained data was evaluated using Student's t-test.

Results

The results of determining the water content under the canopy of a 90-year-old stand are shown in the Table 1. The data shows that in the upper 50-cm soil layer at the three studied locations, the quantitative indicators of water reserves had insignificant differences (Student's criterion 0.2-2.7). In particular, at the location without signs of trampling, a 50-cm layer of gray forest soils contained 476.2 ± 5.79 m^3/ha of water. At the same time, on the section of the path, which has been used as intended for more than 30 years, the water reserves in the 50-cm soil layer were 5.3% higher than on the "control" and amounted to 501.6 ± 7.46 m³/ha, which, in our opinion, is due to the lack of water transpiration by plants within the path, and at the location where the path was decommissioned 15 years ago, the difference with the "control" was only 1.6%, which in quantitative terms is identified by the indicator 483.9 ± 7.66 m³/ha and is associated with physiological by the consumption of water by the plants inhabiting the path space.

Table 1. Water content in the upper 50-cm layer of gray forest soils formed on loess-like loams

Depth of determination, cm	Under the canopy of a 90-year-old plantation, composition* 1Qr2Cb4Bp2Ap1Tc						
	(1) without signs of trampling, "control", m³/ha	part of the path that:					
		(2) used for more than 30 years, m³/ha	relatively "control"		(3) unused for 15 years, m³/ha	relatively "control"	
			%	t		%	t
0-5	67.0 ± 5.09	73.6 ± 2.82	109.8	1.1	64.7 ± 1.78	96.6	0.4
5-10	74.6 ± 1.49	83.9 ± 4.32	112.4	2.0	73.3 ± 1.03	98.2	0.7
10-15	50.0 ± 3.04	47.7 ± 1.94	95.4	0.6	51.2 ± 0.79	104.2	0.4
15-20	46.2 ± 1.86	46.6 ± 3.14	100,9	0.1	46.7 ± 0.30	101.1	0.3
20-25	37.3 ± 1.66	38.8 ± 1.57	104.0	0.7	39.3 ± 1.02	105.4	1.0
25-30	39.8 ± 1.36	41.6 ± 2.98	104.5	0.6	40.4 ± 0.92	101.5	0.4
30-35	38.9 ± 3.57	41.5 ± 1.72	106.9	0.7	41.1 ± 0.88	105.6	0.4
35-40	39.7 ± 1.24	43.4 ± 2.54	109.3	1.3	41.6 ± 0.59	104.8	0.6
40-45	38.9 ± 1.11	39.5 ± 1.92	101.5	0.3	40.9 ± 1.01	195.1	1.3
45-50	43.8 ± 3.38	45.0 ± 1.28	102.7	0.3	44.7 ± 1.20	102.0	0.2
∑ 0-50	476.2 ± 5.97	501.6 ± 7.46	105.3	2.7	483.9 ± 7.66	101.6	0.8

Note: *) Qr – *Quercus robur* L.; Cb – *Carpinus betulus* L.; Bp – *Betula pendula* Roth.; Ap – *Acer platanoides* L.; Tc – *Tilia cordata* Mill. Table value of quantiles of Student's test (t) at probability level 0.05-2.8
Source: developed by the authors

Determination of water saturation coefficients of cracks in the upper 50-centimeter soil layer (Table 2) showed that at the time of the survey, their field indicators were outside the optimal values typical for woody plants (0.80), and significant differences between the obtained values were traced up to 45-centimeters deep. At the location 1 ("control"), the coefficients of water saturation of cracks were in the range of 0.13-0.23 units, and on the exploited path they were 22.2-87.0% higher than on the "control". At the location where the path has not been operated for the last 15 years, the difference between the saturation coefficients compared to the "control" was smaller and amounted to 16.7-66.7%. It is also worth noting that the studied sites are located at highland (155-160 m above sea level), and therefore, the mode of providing them with water resources occurs exclusively due to atmospheric precipitation and significantly depends on their presence or absence, as well as on their frequency of precipitation, intensity and duration in time. The rate of water seepage in different locations of anthropogenic trampling of the path is shown in the Table 3.

Table 2. Coefficient of saturation of cracks with water in the 50-cm soil layer, volume %

Depth, cm	Under the canopy of a 90-year-old plantation, composition 1Qr2Cb4Bp2Ap1Tc						
	(1) without signs of trampling, "control", %	part of the path that:					
		(2) used for more than 30 years, %	relatively "control"		(3) unused for 15 years, %	relatively "control"	
			%	t		%	t
0-5	0.21 ± 0.008	0.39 ± 0.006	185.7	18.0	0.26 ± 0.004	123.8	4.5
5-10	0.23 ± 0.006	0.43 ± 0.006	187.0	25.5	0.34 ± 0.005	147.8	14.1
10-15	0.18 ± 0.004	0.24 ± 0.006	133.3	8.3	0.30 ± 0.004	166.7	5.0
15-20	0.16 ± 0.004	0.23 ± 0.006	143.8	9.7	0.26±0.003	162.5	20.0
20-25	0.16 ± 0.004	0.20 ± 0.008	125.0	4.5	0.22 ± 0.002	137.5	13.3
25-30	0.17 ± 0.003	0.20 ± 0.006	117.6	4.5	0.21 ± 0.002	123.5	11.1
30-35	0.17 ± 0.003	0.21 ± 0.009	123.5	4.2	0.21 ± 0.003	123.5	9.5
35-40	0.13 ± 0.002	0.23 ± 0.007	176.9	13.7	0.20 ± 0.002	153.8	25.0
40-45	0.18 ± 0.004	0.22 ± 0.002	122.2	8.9	0.21 ± 0.002	116.7	6.7
45-50	0.21±0.005	0.22±0.003	104.8	1.7	0.22±0.004	104.8	1.6

Note: table value of quantiles of the Student's test (t) at a probability level of 0.05-2.8
Source: developed by the authors

Table 3. The rate of water filtration in the upper 10-cm layer of gray forest soils

Object number	The place of determination, under the canopy of a 90-year-old tree stand, composition 1Qr2Cb4Bp2Ap1Tc	Depth of determination, cm	Water filtration rate, mm/h	Relatively "control"	
				%	t
1	Location – without signs of trampling "control"	0-5	226 ± 6.9	100.0	-
		5-10	191 ± 5.0	100.0	-
Locations – part of the path:					
2	which has been used as intended for more than 30 years	0-5	22 ± 0.7	9.7	29.4
		5-10	18 ± 0.7	9.4	34.3
3	15 years after the end of its intended use	0-5	76 ± 1.2	33.6	21.4
		5-10	78 ± 1.9	40.8	21.1

Note: table value of quantiles of the Student's test (t) at a probability level of 0.05-2.3
Source: developed by the authors

The data of Table 3 indicate that the compaction of the upper 10-cm layer significantly affects their ability to absorb and filter water. Thus, at the location 1, in our case the "control", it was the "best" rate of water filtration, and its quantitative indicators were in the range of 191 ± 5.0 - 226 ± 6.9 mm/h and significantly prevailed (t = 21.1 - 34.3). The rate of water filtration on the path, where the compacted soils were characterised by "unsatisfactory" filtration, which was in the range of 18 ± 0.7 - 22 ± 0.7 mm/h, and this was only 9.4-9.7% of the values obtained on "control". Removal of a part of the path from operation (location 3) shows that over a 15-year period compacted gray forest soils are only able to partially restore the rate of water filtration (up to 76 ± 1.2 - 78 ± 1.9 mm/h) in a natural way, and this is 33.6-40.8% of the indicators characterizing the control location and convincingly indicates the need to develop more effective measures related to the prevention of anthropogenic trampling on soil compaction.

The upper 10-centimeter layer of gray forest soils within the existing path was characterised by a lower rate of water filtration (by 10 times) than locations without signs of trampling, and this significantly increased the probability of the occurrence and development of erosion processes. At the same time, during heavy rains or downpours, water erosion centres began to form on the edges of the path, where the soil was less compacted than in the central parts of the path. With increasing angles of inclination of the soil surface on the path and with the concentration of water flows, the entire trampled part of the path can be eroded.

As evidenced by the data shown in Figure 2, anthropogenic trampling causes significant changes in the ratio of solid particles, air and water in their upper 45-cm layer (t = 3.0-42.7) and negatively affects its population with physiologically active (fine) roots. In particular, at the first location without signs of the aboveground cover (Fig. 2a), the content of hard particles per unit of soil volume have been varied from 65.0 ± 0.90 till 77.2% ± 0.32. At the same time, cracks were characterised by fairly good aeration (18.6 ± 0.35 - 27.7 ± 0.98%) and insufficient water saturation (3.2 ± 0.07 - 7.3 ± 0.09%). It was at this location, in the 50-cm soil layer of the 90-year-old stand under study, the highest content of physiologically active roots (1087 ± 5.5 g/m^2), of which 72% of roots mastered the upper 15-cm layer.

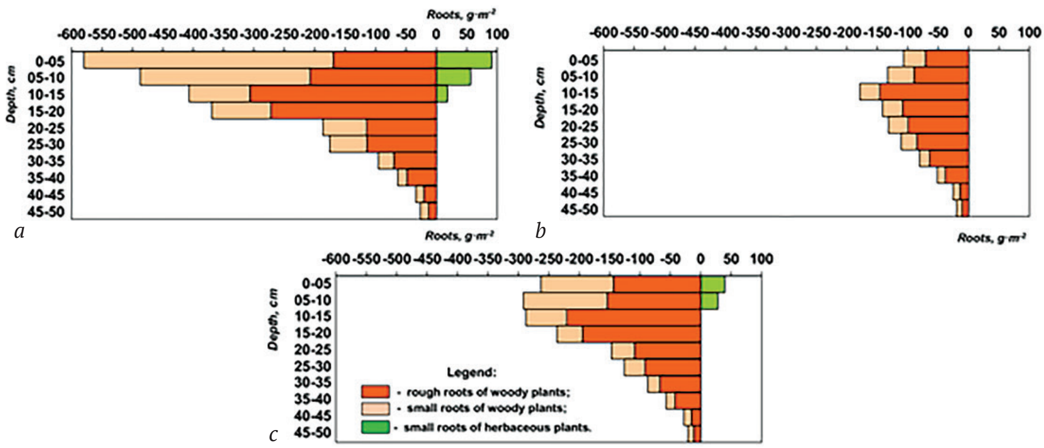

Figure 2. The content of hard particles, air, and water in the 50-cm layer of soils and its population with fine roots at the locations

Note: a) without visible signs of trampling of the topsoil; b) part of the path used by pedestrians for more than 30 years; c) part of the path that has not been used for the last 15 years

Source: developed by the authors

During the study at the first location, it was found out that of the available 1943.4 g/m^2 coarse roots of the birch in the upper 20-cm layer of light gray forest soil, 50.8% belonged to the dead, which is actually the main reason for the presence of dead trunks of the birch on the site, with root systems that have completely fallen out of the soil. The accounting of existing roots with the involvement of the monolith method showed (Fig. 3) that their largest mass (2423.9 ± 3.79 g/m^2) was observed in the upper 50-centimeter layer at the control location (Fig. 3a). Of the total mass of roots belonging to woody plants, the fraction of fine roots was 44.9% (1088.3 ± 5.43), and coarse – 55.1% (1335.6 ± 4.58 g/m²). At the same time, the largest mass of fine roots (410.2 ± 6.73 g/m²), which was 37.7% of their total mass, in the upper 5-centimeter layer have been recorded.

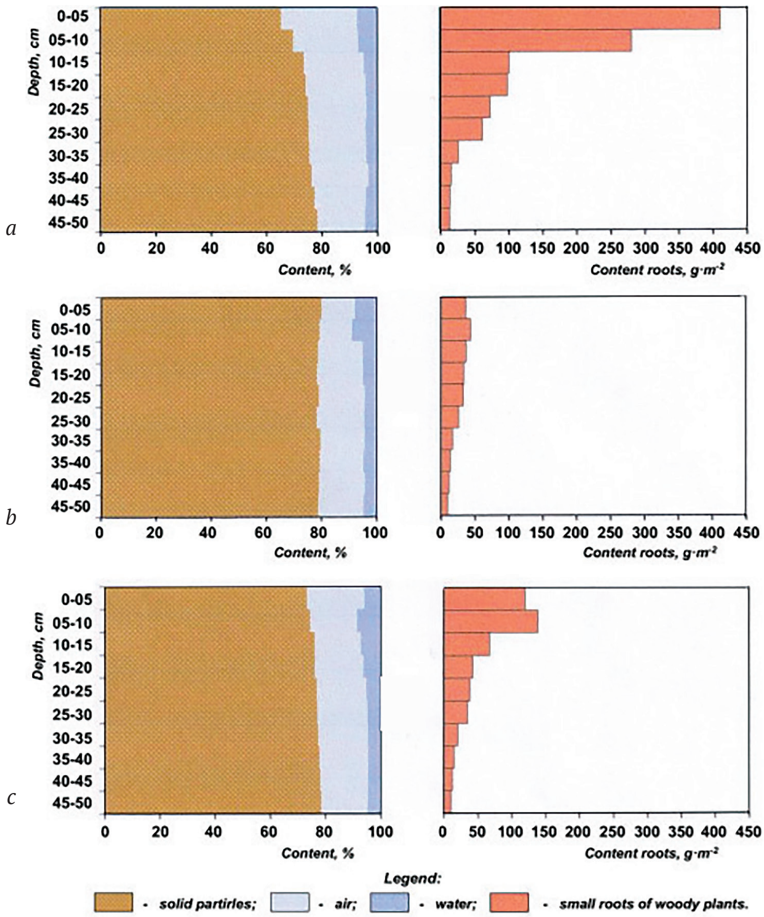

Figure 3. Inhabitation by roots of the upper 50-centimeter soil layer at locations
Note: a) without visible signs of trampling of the topsoil; b) part of the path used by pedestrians for more than 30 years; c) part of the path that has not been used for the last 15 years
Source: developed by the authors

Coarse roots dominated the 10-15 cm soil layer (Fig. 3a, 3c). Their share, from the total mass of available roots, was 22.9% (306.5 ± 8.50 g/m²). The bulk of the available roots (74.0%) grew in the 20-cm layer of the soils. Roots of herbaceous plants, dominated by *Carex pilosa* Scop. and *Asarum europaeum* L., mastered the upper 15-centimeter layer. The mass of their roots was 165.3 ± 1.35 g/m², which was 4.8 times less than the fine roots of trees that inhabited the same soil layer. The maximum share of the mass of the roots of grass plants (55.1%) was recorded at this location was in the 0-5 cm layer. With depth, the content of roots decreased to 34.0% in the 5-10-cm layer and to 10.9% in the 10-15-cm layer.

At the second location, where a part of the path has been used for more than 30 years (Fig. 3b), the action of anthropogenic trampling significantly affects the population of the 50-centimeter layer of soil ($t_f = 276.9$). After all, their mass decreased by 40.6% compared to the "control" and during the experimental work, it was identified at the level of 983.4 ± 3.56 g/m^2. Trampling had a particularly unfavourable effect on the development of fine roots in woody plants. Their mass, in comparison with the "control", decreased by 4.3 times and amounted to only 275.9 ± 0.45 g/m^2. Coarse roots, more resistant to soil compaction, this is indicated by their mass (725.5 ± 3.25 g/m^2), which decreased in comparison with the "control" by 1.8 times. It is also worth noting that there were no herbaceous plants at this location, and the fine roots of woody plants, in order to master the compacted layers of the soil, penetrated them through the dead fragments of coarse roots (Fig. 4).

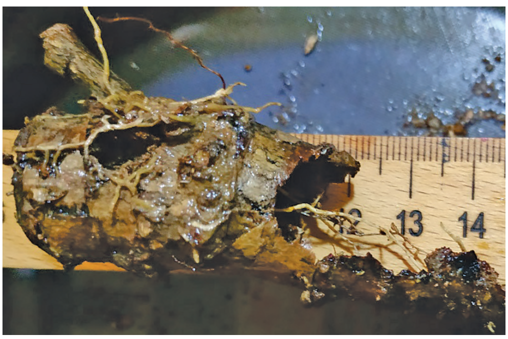

Figure 4. Fine roots of woody plants growing in a fragment of a dead coarse root (second location)
Source: authors' photo

At the third location, where a part of the path has not been used for the last 15 years (Fig. 1c), certain changes related to the improvement of the ecology of the environment took place during this period. In particular, herbaceous plants settled on the site, among which *Asarum evropaeum* L. and *Impatiens parviflora* DC. occupied a dominant position. *Pulmonaria oficinalis* L. and *Lamium galeobdolon* L. occurred singly. Their height did not exceed 16 cm, and their roots, at the time of the study, mastered only the upper 10-centimeter soil layer. At the same time, the mass of the roots was insignificant and amounted to 67.6 ± 0.87 g/m^2. From this mass, 58.4% of the roots were developed in the 0-5 cm soil layer, and 41.6% – in the 5-10 cm layer.

The total mass of the roots of woody plants inhabiting a 50-cm thick layer of gray forest soils at the third locations was 1545.7 ± 11.20 g/m^2, which was 63.8% of the total mass of roots recorded in the "control" and 23.2% more, than in the second location. Actually, it is by this percentage that the total mass of roots at this location has increased over the past 15 years. At the same time, the mass of fine roots was 45.7% of their mass in the "control" (496.6 g/m^2), and the increase in mass for this root fraction over the last 15 years was 22.0%. The mass of recorded coarse roots was 78.6% of their mass in the "control" (1049.1 ± 13.29 g/m^2), and the increase in the mass of coarse roots over the last 15 years was on the order of 25.2%. Within a 50-centimeter layer of soil, the largest mass of fine roots (3.2 times more than on the existing path) was recorded in a 5-10-centimeter soil layer, and coarse roots (1.5 times more) – in the 10-15-centimeter layer of soil.

In the process of restoring the water-physical properties of gray forest soils, the 7-year-old self-seeding *Umus scabra* deserves special attention, which actually significantly contributed to the increase (by 23.2%) of the root mass within this location. Roots of *Ulmus scabra*, inhabiting excessively compacted surface layers of the soil, loosen them, and hyphae of fungi, which settle on fine roots and form mycorrhiza, facilitate access to seedlings of water, nutrients and minerals. In the soil of location 3, at a depth of 5-10 centimetres it's observed vertically directed soil passages formed by earthworms. The passages were mainly grouped in 3-5 pieces and their diameter reached 6 mm.

In particular, common earthworms, in park phytocenoses, provided that bioturbations are involved, such as digging, production of coprolites, mixing of organic materials and mineral particles, can effectively influence both the physical and biological properties of soils. After all, earthworms, penetrating the soil, build burrows that increase the space of cracks, transport organic matter during the production of coprolites, grind organic materials during their decomposition, and also provide plants with nutrients due to their concentration in the walls processes, change the diversity and contribute to the growth of the activity of microbial communities due to the selective consumption of certain groups of microorganisms.

Discussion

Scientific data related to the content of solid particles, air and water in the upper 50-centimeter layer of gray forest soils, as well as their population with the roots of woody and herbaceous plants, have been expanded and clarified by F. Brovko *et al.* (2023). The obtained data on the water properties of gray forest soils clarify and supplement the information on the water-physical properties of brown mountain forest soils (Lenevych, 2020) and sod-layered soils surveyed in the Oleksandria park, which is located near active roots in the soil layer, due to the prevention of its compaction in the stands of woody plants (Dragan, 2012).

For the gray forest soils exposed within the forests of the dendrology park "Oleksandria", there are compaction changes in the range from 0.85 to 1.59 g/m^3. At the same time, in cells with a density of 1.18-1.36 g/m^3 above-ground grass cover is preserved, and in places with a compaction of 1.46-1.59 g/m^3 – grass cover is absent (Dragan, 2012). According to F. Brovko *et al.* (2023), within the hornbeam groves growing in Holosiivo park, the significant influence of anthropogenic trampling on the compaction of gray forest soils was traced to a depth of 45 cm. At the same time, the maximum rates of soil compaction (38.0% higher than in the control) were characteristic of the upper 0-5 cm layer, and the minimum (4.9%) were observed in the 40-45 cm layer.

Research by P. Teyluk *et al.* (2022) indicates that recreational trampling can lead to changes in the microrelief of territories, which in turn affects the redistribution of moisture. After all, along the paths the soil is compacted and the relief is lowered. A berm is formed along the path, along which water flows during precipitation. This contributes to the development of erosion processes and is manifested in the washing away of soil from its surface, which is also confirmed by our research (Fig. 1b).

Field studies conducted within the examined locations, with different manifestations of the intensity of trampling and compaction of the soil surface, show that the degree of changes in their water and physical properties depends on the combination of individual components of the complex of ecological factors that dominate within the path. At the same time, their manifestation usually occurs due to a violation of the water-air regime of soils, a decrease in porosity and water content in their upper soil layers (Korkanç, 2013).

Research by S.A. Lei (2004) quantitatively investigated the impact of various recreational activities on soil properties in a blackbrush (Coleogyne ramosissima) shrubland. The findings indicated that human trampling, biking, and off-road motor vehicle traffic adversely affect soil properties by compacting the soil, leading to reduced porosity and increased soil penetration resistance. Research confirms the conclusion of O. Lenevych (2020) that within the path, in the absence of anthropogenic influence, the soil that has undergone degradation processes is able to restore its natural state over time.

In particular, the water content in the upper 50-cm layer of gray forest soils, at the time of the study, on the active path was 501.6 ± 7.46 m^3/ha, and on the decommissioned path – 483.9 ± 7.66 m^3/ha. The water content within the 5-centimeter layers of the soil profile differed from its values obtained in the "control". On the path that has been in use for more than 30 years, the difference was 1.5-12.4%, and on the path that was decommissioned 15 years ago, the difference was smaller and was at the level of 1.1-5.6%. However, the obtained values of the Student's criterion (t = 0.2-2.7) indicate the absence of a significant difference between the indicators of water content at the studied locations. The numerical values of the water content (476.2 ± 5.97 - 501.6 ± 7.46 m^3/ha and the coefficients characterizing the saturation of cracks with water 0.13-0.43 units, recorded in the upper layers of the 50-centimeter soil layer, were beyond the optimal values (0.80 units) and indirectly indicated the dependence of their water regime on the presence or absence of atmospheric precipitation, its duration and frequency.

F. Brovko *et al.* (2023) researched that the highest indicators of anthropogenic trampling were observed on the path, which was used as intended for more than 30 years, namely in its upper 10-centimeter layer, where the soil (compared to the location without signs of trampling) had a 32.1-38.0% higher compaction and correspondingly, the content is smaller by the same percentage. The content of solid particles per unit volume of soil was higher by 14.1-22.8%, and the population of the studied layer by fine roots of woody plants was lower by 84.6-91.2%.

The water permeability of the soil, in this layer, had the lowest indicators, because the rate of water filtration was at the level of 18-22 mm/h, which is 90.3-90.6% less than in the control. Under the certain environmental conditions that can cause a threat from the development of erosion processes on the paths, with similar soil compaction. The given data are consistent and do not contradict the data obtained on the path network of the "Boykivshyna" National Nature Park (Lenevych *et al.*, 2023).

The infiltration resistance and water penetration were most sensitive to soil compaction, as also confirmed by studies conducted A. Ferrero & J. Lipiec (2000). They indicated that the decrease in hydraulic properties in the most compacted soils occurred due to lower macroporosity.

It is also worth noting that at the location where a part of the path has been operated for more than 30 years, in the upper 50-cm layer of gray forest soils, the total mass of the roots that populated them was 983.4 ± 3.56 g/m^2, and this is only 40.6% of the total mass of roots recorded at the studied location without signs of trampling. At the same time, the share of fine roots inhabiting this layer of soil was much smaller (23.7%) than coarse roots (54.3%), and their mass was at the level of 257.9 ± 0.45 g/m^2 and 725.5 ± 3.25 g/m^2 respectively. Such ratio between the fractions of the investigated roots, as evidenced by Z.H. Kalahroudi *et al.* (2023) associated with mechanical damage and death of part of fine roots as a result of over-compaction of the upper soil layers.

After the cessation of anthropogenic trampling, the natural processes of restoration of degraded soils, as it happened in our case, at a location where the path has not been used for the past 15 years, begin within the path. The restoration begins with the fall of leaves on the surface of the path and continues thanks to the formation of the forest litter on it, its settlement by self-seeding *Ulmus scabra* and the appearance of earthworms in the surface layer of the soil. Intensification of processes, as noted by

O. Lenevych (2020), occurs in the autumn-winter period, during the greatest fluctuations in the temperature regime on the soil surface and is mostly associated with freezing or thawing of the soil in its upper layers. The changes in the physical properties of the upper 10-cm layer of light gray forest soils after trampling stopped indicate that during the last 15 years, at this location (compared to the part of the path where the soil has been trampled for more than 30 years), there has been an improvement in their quantitative and relative indicators. In particular, as evidenced by F. Brovko *et al.* (2023), there was a decrease in soil compaction (by 16.9-19.5%) and the content of solid particles per unit volume (by 6.2-9.9%), as well as an increase in the percentage of cracks per unit volume of soil (by 23.6-39.1%) and the mass of fine roots of woody plants (by 3.2-3.3 times).

At the location where the path has been trampled for more than 30 years, the upper 10-centimeter soil layer contained 31% of fine roots, compared to their mass recorded in the 50-centimeter soil layer (255 ± 0.4 g/m^2), and at the location where the path was not trodden during the last 15 years, the content of fine roots of woody plants was higher (51%), and their mass in a 50-cm soil layer was 495 ± 5.1 g/m^2. Evaluating the total content of the roots of woody plants in a 50-centimeter layer of soil, at a location where the path has not been trampled for the past 15 years, it should be noted that the total mass of roots exceeded the mass of roots recorded at a location where the soil had been trampled for 30 years by 57.2%, and their mass was 1545.7 ± 11.20 g/m^2. The mass of fine roots prevailed by 92.6% and was at the level of 496.6 ± 5.09 g/m^2, and the mass of coarse roots was greater by 44.6% and was estimated at 1049.1 ± 13.29 g/m^2. The data indicate that the main mass of fine roots of woody plants master the upper 10-centimeter soil layer and do not contradict the quantitative and relative indicators obtained for sod-layered soils (Ryzhov & Brovko 2014).

Thus, at the studied locations, the moisture regime of gray forest soils is formed due to atmospheric precipitation. At the same time, water reserves in the upper 50-centimeter layer of soils under the canopy of the studied stand, both in the cells that were not trampled and within the paths, did not have significant differences, and a significant impact of trampling on the content of solid particles, water, air and roots of woody plants in the soil was traced to a depth of 40 centimeters.

Conclusions

The quantitative indicators of water reserves in the upper 50-cm layer of gray forest soils under the canopy of the studied 90-year-old stand at the three surveyed locations were marked by insignificant differences (Student's criterion t = 0.2-2.7). In particular, at the location without signs of trampling, the water content was observed at the level of 476.2 ± 5.79 m^3/ha, at the location where the path has been used for its purpose for more than 30 years, the water reserves were 5.3% higher, and at the location where the path was removed from operation 15 years ago, the difference was at the level of 1.6%.

The coefficients of water saturation of the cracks in the upper 50-centimeter soil layer were beyond the optimal values (0.80), and significant differences between the obtained coefficients were observed up to a depth of 45 cm. At the location without visible signs of trampling, the coefficients of saturation of cracks with water were within 0.13-0.23 units, and on the exploited path they were 22.2-87.0% higher. At the location where the path has not been exploited for the past 15 years, the difference between the coefficients saturation, in comparison with the first location, was lower and amounted to 16.7-66.7%.

The most intensive water filtration was observed at the location without visible signs of trampling and was 191 ± 5.0 - 226 ± 6.9 mm/h. At the location where the path was in use for more than 30 years, water filtration rates were only 9.4-9.7%, and at the location where the path was decommissioned 15 years ago, water filtration rates were 33.6-40.8% of the rates obtained at the control location.

It was found that under the influence of anthropogenic trampling, there are significant changes in the ratio of solid particles, air and water in their upper 45-centimeter soil layer (t = 3.0-42.7), and the lowest content of solid particles (65.0 ± 0.90 - 77.2% ± 0.32 per unit volume of soil), was observed at the first location, without visible signs of trampling of the topsoil. In the second and third locations, where the soils were trampled, the content of solid particles per unit volume of soil was 2.2-22.8% and 1.0-10.6% respectively higher than in the first location.

The largest mass of roots (2423.9 ± 3.79 g/m^2) was observed in the upper 50-cm layer, at the location, without visible signs of trampling of the topsoil. Of their total mass, the fraction of fine roots was 44.9%, and coarse roots – 55.1%.

It's worth continuing research related to the elucidation of the dynamics of natural overgrowth of trampled space with woody and herbaceous plants, as well as the dynamics of restoration of soil density, solid particle content, pores, and roots of vegetation in the studied plantation.

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Conflict of Interest

None.

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Водно-фізичні властивості сірих лісових ґрунтів та їх коренезаселеність в осередках антропогенного витоптування

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Анотація. Метою досліджень стало виявлення впливу антропогенного витоптування сірих лісових ґрунтів на уміст у них вологи, повітря, твердих часток та маси дрібних і грубих коренів. Уміст води і водопроникність ґрунтів визначали за загальноприйнятими методиками, а вміст твердих часток, води і повітря в одиниці об'єму ґрунту – за допомогою мірних циліндрів. Заселення ґрунту коренями визначали методом «монолітів». З'ясовано, що під впливом антропогенного витоптування запаси води у верхньому 50-сантиметровому прошарку ґрунтів були на 1,6-5,3 % більші, ніж під 90-річним дубово-грабовим насадженням без видимих ознак деградації, а коефіцієнт насичення ґрунту водою, під час проведення досліджень, був нижчим (0,21-0,43 %) за оптимальні значення (0,80 %). При цьому, найбільших деградаційних змін досліджені фізичні показники зазнавали у верхній 10-сантимеровій товщі сірих лісових ґрунтів. Тут було зафіксовано збільшення умісту твердих часток ґрунту (на 14,1-22,8 %), а також зменшення об'єму шпарин (на 32,0-44,3 %)

та маси фізіологічно активних коренів деревних рослин (на 84,6-91,2 %). Показано, що у разі припинення витоптування поверхні стежки, природне відновлення деградованих фізичних показників в ущільнених ґрунтах найінтенсивніше відбувається у верхній 5-сантиметровій товщі. При цьому, за 15-річний період, спостерігалися зміни у зменшенні умісту твердих часток (на 9,9 %), збільшенні умісту шпарин (на 39,1 %) та фізіологічно активних коренів деревних рослин (на 330,0 %). Наукова новизна полягає в тому, що отримані кількісні та відносні показники умісту в антропогенно-ущільнених ґрунтах твердих часток, повітря та води пояснюють особливості його заселення коренями деревних і трав'яних рослин, а також свідчать про прикладне значення результатів, представлених у дослідженні

Ключові слова: ущільнення ґрунту; водопроникність; паркові насадження; надземний покрив; заселення ґрунту коріннямвологе середовище; коливання температури та вологості; руйнівне навантаження

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Monitoring economic risks associated with forest landscape degradation

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Abstract. The study aimed to assess the economic risks caused by the degradation of forest landscapes and their impact on the forestry sector's economy and regional development. The analysis examined the impact of deforestation, soil erosion, biodiversity loss and climate change on forestry

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sustainability, the labour market, investment attractiveness and financial flows in the regions. A comprehensive approach was used, including statistical analysis of data, comparative assessment of changes in the forest industry, and forecasting of possible economic consequences under different scenarios. The study found that between 2015 and 2024, global forest cover loss reached 10 million hectares annually, leading to a reduction in timber stocks and a 15-25% increase in prices in the most affected regions. The decline in forest area has had a direct impact on employment in the forestry industry, causing a 20-30% reduction in jobs in the sector in Southeast Asia and Latin America, where logging is an important source of income. The results show that the reduction in tax revenues from the forestry industry and the shrinking of local budgets have led to limited funding for social programmes and infrastructure projects in rural areas. The analysis also showed that illegal deforestation remains a serious problem, as up to 30% of the global timber market may be of illegal origin, undermining the economic stability of the industry and complicating international regulation. The loss of biodiversity and soil erosion has led to an increase in the cost of ecological restoration of forest areas, which in some countries has exceeded USD 5 billion. Comprehensive measures to reduce economic risks are proposed, including the introduction of strict regulatory mechanisms, the development of FSC certification, stimulating investment in forest restoration, and the introduction of digital monitoring technologies, including satellite surveillance and the use of drones. The results of the study can contribute to the development of strategies for forest management, environmental control, reduction of economic risks, implementation of monitoring technologies and assessment of the impact of forest degradation on regional development

Keywords: environment; sustainable development; ecosystem; erosion; biodiversity

Introduction

The degradation of forest landscapes is one of the most acute environmental and economic problems of our time, affecting the sustainable development of society, ecosystem balance and economic security of regions. Forest ecosystems perform key functions in conserving biodiversity, regulating climate, maintaining water balance and providing natural resources for the economy. However, large-scale deforestation, soil erosion, climate change and anthropogenic pressure pose significant economic risks, which manifest themselves in the reduction of forest resources, loss of jobs, reduced investment attractiveness and increased socio-economic instability.

According to the Food and Agriculture Organisation of the United Nations (n.d.), between 2015 and 2024, the average annual loss of forest area was about 10 million hectares, which led to an increase in the cost of timber, a reduction in production capacity in the forest industry and a decrease in local community income. Illegal deforestation, which accounts for up to 30% of the global timber market, significantly increases financial risks for state budgets, reduces the competitiveness of legal enterprises and exacerbates the problem of the shadow economy in the sector. The consequences of forest degradation are particularly noticeable for countries whose economies are heavily dependent on the forest sector, in particular for countries in Southeast Asia, Latin America and Eastern Europe (Moroz, 2024). The loss of forest areas in these regions has led to a 20-30% reduction in employment in the logging industry, which has led to an outflow of labour to other sectors and increased social instability. In addition, the loss of biodiversity and destruction of soil cover require additional costs for environmental restoration, which in some countries exceed billions of dollars (Soloviy, 2016).

The problem of forest landscape degradation and its economic consequences is the subject of numerous scientific studies. The loss of forest resources causes significant financial losses, reduced employment, and a decline in the investment attractiveness of regions. Assessment of economic risks in this area is relevant, but not sufficiently researched. F. Sourokou *et al.* (2024) noted that economic methods for assessing forest degradation are used to a limited extent, which makes it difficult to develop effective policies to prevent losses. Sustainable management of forest resources is a key tool for their conservation. According to the study by E. Khazieva *et al.* (2022), overgrowth of pastures with shrubs is one of the main signs of landscape degradation. The use of geoinformation technologies allowed the authors to identify the main factors of this process, including changes in land use and climate fluctuations. The emphasis is placed on the need for economic mechanisms to mitigate the negative effects.

Based on the results of E. Duulatov *et al.* (2021), intensive soil erosion leads to a significant reduction in productive forest areas. Modelling using the Revised Universal Soil Loss Equation (RUSLE) methodology allowed the authors to estimate the loss of fertile soil, which complicates forest management and creates economic risks for the logging sector. The environmental consequences of forest degradation are assessed in the work by G. Donbaeva *et al*. (2024). The decline in the populations of animals and plants dependent on forest ecosystems not only increases environmental instability, but also threatens economic sectors such as ecotourism and agriculture.

The reduction in the area of floodplain forests in the Naryn Valley leads to a decrease in the regulatory role of forests in water conservation, as confirmed by N. Degembaeva *et al.* (2022). The study demonstrates the need to strengthen the policy of preserving floodplain ecosystems as a factor in maintaining the stability of the region's water resources. Z. Yu *et al.* (2024), in their work, focused on assessing the risks of land degradation on the Elk Plateau, where significant soil erosion poses a serious threat to agriculture and forestry. The work of A. Ibraimova *et al.* (2023) proves that forest degradation has a direct impact on the well-being of the population that depends on natural resources. In the Chui Oblast of Kyrgyzstan, traditional agricultural and forestry enterprises are losing productivity, forcing local residents to change their activities and look for new economic strategies.

Significant experience in addressing land degradation has been gained in the European Union. As noted by Y.O. Mynko (2024), the integration of modern land management methods and environmental and economic measures can effectively reduce the negative impact of anthropogenic factors. The issue of forest degradation as a result of military operations is considered by A.Y. Herman (2024). War contributes to the destruction of ecosystems, which necessitates costly environmental restoration programmes. The approaches proposed by the author may be useful for the territories affected by military operations. The processes of adaptation to environmental challenges through the introduction of "green" economic strategies are considered by O.S. Chmyr & T.K. Kvasha (2013). The analysis of sustainable development indicators demonstrates the need for multi-level management that takes into account both environmental and socio-economic aspects.

Thus, current research confirms that forest landscape degradation has a multifaceted impact on the economy, environment and social processes. The use of the latest technologies, implementation of regulatory measures, promotion of sustainable forest management and development of international forest conservation programmes are key strategies to overcome the effects of degradation and ensure economic stability of the regions. Therefore, this study provides a comprehensive analysis of the economic risks caused by the degradation of forest landscapes, identifying their impact on the forest sector, employment, regional development and investment attractiveness. Particular attention is paid to the mechanisms for minimising negative economic consequences through the introduction of sustainable forest management, environmental regulation and modern forest monitoring technologies.

Materials and Methods

The main sources of data were the reports of the Food and Agriculture Organization of the United Nations (n.d.), the World Wide Fund for Nature (WWF), and the World Bank (2024), which contain up-to-date information on the dynamics of forest area loss, the economic impact of forest degradation, and the level of employment in the forest industry (Soloviy, 2016).

The methodological basis of the study included several key approaches that allowed for a comprehensive assessment of the economic risks of forest degradation. Firstly, a statistical analysis of data on the scale of deforestation in 2015-2024 was conducted based on official statistics (Food and Agriculture Organization of the United Nations, n.d.; Soloviy, 2016). Data on deforestation rates in South America (Brazil, Paraguay), Asia (Indonesia), Africa (Democratic Republic of Congo, Nigeria, Ghana), Europe (Ukraine, Romania, Finland, Sweden), and North America were used, as these regions demonstrate different forest management models and have a significant impact on global deforestation processes. In South America, deforestation is driven by agricultural expansion, in Asia by palm oil production, and in Africa by illegal logging and agricultural development. The choice of European countries allows us to compare the consequences of illegal logging (Ukraine, Romania) and the effectiveness of sustainable forest management (Finland, Sweden). We also examine trends in employment in the logging sector and the dynamics of timber prices in these regions.

Economic forecasting methods were used to assess the economic consequences of forest degradation. Three possible scenarios for the development of the forestry sector were modelled: a pessimistic scenario that assumes uncontrolled deforestation, a baseline scenario that reflects current trends, and an optimistic scenario that assumes the introduction of effective mechanisms for monitoring and restoring forests. Economic modelling allowed us to estimate possible changes in tax revenues, investment activity, and the overall impact of the decline in forest resources on the gross domestic product (GDP) of the regions.

Geoinformation analysis played an important role in the study, as it made it possible to visualise the degradation of forest landscapes. For this purpose, satellite images and map data were used to identify the regions with the most intense deforestation. Particular attention was paid to the analysis of illegal logging, which remains one of the main causes of economic instability in the forest sector.

The comparative analysis examined the effectiveness of various forest management strategies, such as the Forest Stewardship Council International (n.d.) certification system, environmental taxation, and the development of alternative sources of income, including ecotourism and recreational use of forests. International experience in combating illegal logging was assessed, including an analysis of carbon credit mechanisms, the Regulation (EU) No. 995/2010 of the European Parliament and of the Council "Laying down the obligations of operators who place timber and timber products on the market Text with EEA relevance" (2010) and the Soy Moratorium (2024).

Modern methods of assessing the ecological state of forest ecosystems were used to monitor biodiversity. The use of automated camera traps provided data on changes in wildlife populations, and deoxyribonucleic acid (DNA) analysis of soil samples made it possible to assess changes in the microflora of forest soils. The classical Shannon and Simpson indices were used to quantify biodiversity, which made it possible to assess the impact of forest degradation on ecological balance.

Scenario analysis allowed us to assess the possible consequences of changes in forestry policy. The impact of regulatory measures on regional economies, employment levels, and the prospects for the development of green technologies that could reduce the economy's dependence on timber harvesting was considered.

Results

The impact of deforestation on the economy of the forest sector

The degradation of forest landscapes caused by deforestation, soil erosion and biodiversity loss have a significant impact on the forestry sector's economy and regional development. According to the Food and Agriculture Organization of the United Nations (n.d.), in the period from 2015 to 2020, global forest cover loss was approximately 10 million hectares annually, and this trend continued to grow in the following years. This leads to a decrease in available timber reserves, which in turn leads to higher prices for timber. Figure 1 illustrates the dynamics of forest cover loss over the period 2015-2024.

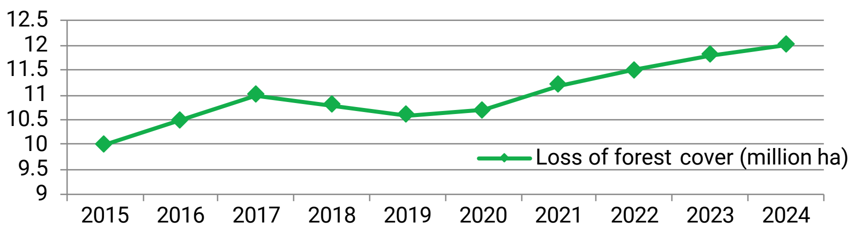

Figure 1. Dynamics of forest cover loss (2015-2024)

Source: compiled by the authors based on source Food and Agriculture Organization of the United Nations (n.d.)

The decline in forest resources directly affects employment in the forest industry. According to the World Bank (2024), the reduction in forest areas and timber harvesting leads to a decrease in demand for labour in this sector. This is especially noticeable in regions where the forest industry is the main source of employment. Between 2010 and 2020, South America lost approximately 2.6 million hectares of forest annually, which negatively impacted employment in the forestry sector. More than 90 per cent of people living below the poverty line depend on forests for food, firewood, and livelihoods.

Using satellite images from NASA and European Space Agency (2023), combined with GIS analysis, the most critical deforestation areas were identified for the period 2015-2024 (Global Forest Watch, n.d.). According to the analysis, the largest losses of forest cover were observed in the Amazon (about 1.2 million hectares annually, Indonesia (900 thousand hectares), and

Central Africa (650 thousand hectares). Cartographic models visualised the dynamics of changes in forest cover, which showed the unevenness of the deforestation process. In particular, in Europe, a significant reduction in forest area was recorded in the Carpathian region (Ukraine, Romania), where about 400 thousand hectares of forest were lost between 2015 and 2024 due to active logging and insufficient control over illegal logging (Soloviy, 2016; Miniaylo *et al.*, 2020).

An assessment of economic losses showed that the reduction in forest areas directly affected the timber market and employment in the industry. In Southeast Asia, the reduction of forest resources has led to a 20-30% increase in the cost of timber, which has led to a reduction in production capacity in the woodworking industry (Food and Agriculture Organization of the United Nations, n.d.). In Latin America, losses from illegal logging are estimated at USD 5-7 billion annually, and in Africa at USD 3-4 billion (World Bank, 2024). In countries with strict forestry control mechanisms in place (e.g., under the European Timber Regulation (EUTR)), the situation has stabilised. In particular, in Finland and Sweden, illegal logging does not exceed 5% of the total volume of timber harvesting, while in Brazil and Indonesia this figure reaches 30-40% (EU rules against…, n.d.).

A comparative analysis of international initiatives, such as the Amazon Soy Moratorium and the EUTR, has shown that their implementation helps to reduce deforestation. For example, after the introduction of the Amazon Moratorium in 2006, deforestation rates in Brazil decreased by 84% in certified areas (Soloviy, 2016). In the European Union (EU), the share of illegal timber in imports decreased by 15% in 2023 after the EUTR requirements were tightened (EU rules against…, n.d.). However, in countries where control mechanisms remain weak (e.g., Nigeria, Ghana, and Paraguay), illegal logging continues to grow, undermining the economic stability of the industry and increasing financial risks (Food and Agriculture Organization of the United Nations, n.d.).

Reduced logging has a negative impact on local budgets, which leads to reduced funding for social programmes. In Canada, where the forestry industry generated USD 34 billion in 2013, the decline in logging has led to a reduction in funding for education and healthcare in rural communities (World Bank, 2024). In Ukraine, the decline in timber exports (USD 507 million in 2004) affected budget revenues, which affected the financing of schools and hospitals (World Bank, 2024). In Latin American countries (Brazil, Chile), the annual loss of 2.6 million hectares of forest has reduced community incomes, forcing governments to cut spending on healthcare, education, and infrastructure (Green Climate Fund…, 2021). According to the WWF, deforestation and forest degradation in tropical regions have a direct impact on the health and well-being of local communities (Soloviy, 2016). Figure 2 shows a visual comparison of GDP losses in different regions of the world due to forest degradation.

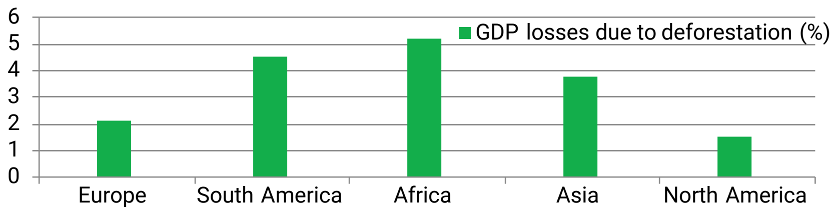

Figure 2. The impact of deforestation on regional GDP

Source: compiled by the authors based on I. Soloviy (2016)

Thus, deforestation has a complex negative impact on regional development, reducing budget revenues, reducing employment and slowing economic growth. This confirms the need to develop effective forest management strategies that combine economic and environmental interests.

A comparative analysis of the Forest Stewardship Council (FSC) certification policy has shown that its implementation helps to reduce illegal logging, increase transparency of the timber market and attract investment in the sustainable development of the forest sector. In the EU, more than 50% of commercial timber is certified according to FSC standards, which ensures stable market conditions and promotes the growth of forest products exports (Food and Agriculture Organization of the United Nations, n.d.). At the same time, in countries with a low level of certification, such as Ukraine, Romania, and Indonesia, illegal logging remains a serious problem that negatively affects financial flows and investment attractiveness of the industry (Soloviy, 2016). An analysis of economic indicators has shown that countries with a developed FSC certification system (Finland, Sweden, Canada) have a stable level of employment in the forest industry, while in regions with a low level of certification (Brazil, Paraguay, Ghana), the number of jobs in the industry has decreased by 15-25% due to illegal logging and a shrinking resource base (World Bank, 2024).

Instability in the forestry sector caused by the degradation of forest resources reduces its investment attractiveness. The depletion of forests leads to a reduction in available timber reserves, making long-term investments risky. According to the Food and Agriculture Organization of the United Nations (n.d.), about 10 million hectares of forest disappear every year worldwide, which negatively affects the availability of raw materials for the forest industry. In regions with high deforestation rates, such as the Amazon, Central Africa, and Southeast Asia, there is a gradual withdrawal of investors who fear a shortage of timber in the future (Flatpacked forests..., n.d.).

Climate change, including rising average temperatures, changes in precipitation and more frequent natural disasters (fires, floods), contribute to the degradation of forest landscapes, which in turn affects the economic stability of the regions. Forest fires, floods, and droughts cause significant economic losses. For example, in 2021, large-scale fires in the United States destroyed more than 2.2 million hectares of forest, resulting in billions of dollars in losses and a number of companies' refusal to invest in the region (National Integracy Fire Center, 2025).

Another important factor that reduces the investment attractiveness of the industry is the spread of illegal logging. Illegal deforestation creates an unstable business environment and can also lead to sanctions and trade restrictions from international markets. According to the WWF, up to 30% of timber in global circulation may be of illegal origin, which undermines confidence in the industry and makes it less attractive to international investors (Soloviy, 2016). Large corporations avoid investing in regions where government control over logging is weak, fearing reputational risks and legal complications.

Reduced investment in the forestry industry leads to a general slowdown in its development, especially in the area of technological modernisation. Projects to introduce zero-waste production, automate timber harvesting, and create new logistics centres are being halted due to a lack of funding. For example, in Southeast Asia, more than 15% of woodworking plants closed in 2015-2024 due to the depletion of forest resources and a lack of stable supplies of raw materials. In Africa, low levels of investment in forest infrastructure hinder local economic development and job creation (World Bank, 2024).

Lack of funding also hinders the development of environmental technologies in forestry. Investors are reluctant to invest in the research and development of biotechnology for forest restoration, satellite deforestation monitoring systems, and other innovative solutions. In 2021, global investments in green technologies in the forestry sector decreased by 15%, which slowed down the implementation of many sustainable forest management projects (World Bank, 2024). This could lead to further deterioration of forests and an even greater reduction in investment in the future.

In order to overcome investment risks, international financial institutions and environmental organisations are developing mechanisms to support the sustainable development of the forest industry. The World Bank (2024) and the Green Climate Fund (GCF) have allocated more than USD 500 million to finance environmental initiatives in the forest industry aimed at reducing deforestation, restoring degraded forests, and developing alternative sources of income for local communities (Green Climate Fund Board..., 2021). In addition, the European Investment Bank (EIB) (n.d.) also provides loans and grants to support sustainable forest management programmes, particularly in developing countries (Indonesia, Brazil). In 2023, the international LEAF Coalition initiative raised USD 1.5 billion from governments and the private sector to protect tropical forests and support local communities dependent on forestry (LEAF Coalition commitments..., 2022). In addition, the introduction of international environmental standards, such as Forest Stewardship Council International (n.d.) and Programme for the Endorsement of Forest Certification (PEFC) (n.d.) certification, helps to increase the transparency of the logging business, combat illegal logging, and attract responsible investors. Many governments in the European Union, Canada, and the United States are tightening requirements for timber imports, giving preference to products that meet these certification standards. This encourages companies to switch to environmentally responsible forest management and ensures the long-term financial stability of the forestry sector.

Factors causing instability in the forestry sector include variability in regulatory policies, increased illegal logging, and changes in demand for timber. This reduces the investment attractiveness of the industry, as companies assess the increased risks of investing in regions with unstable forest management. The high level of risks associated with resource depletion, natural disasters and illegal logging makes investors look for more reliable industries to invest in. This, in turn, slows down the development of the forestry industry, reduces investment in technology and leads to further environmental degradation. To stabilise the situation, it is necessary to strengthen national and international control over logging, encourage environmentally responsible business and create financial mechanisms to compensate for investment risks.

Violations of environmental regulations and illegal logging can have serious financial consequences for forestry companies. Governments in many countries, including the United States, Canada, Germany, France, the United Kingdom, Brazil, Indonesia and Australia, are introducing strict regulatory mechanisms to combat illegal logging and ecosystem degradation. For example, in the European Union, Regulation (EU) No. 2023/1115 of the European Parliament and of the Council "On the Making Available on the Union Market and the Export from the Union of Certain Commodities and Products Associated with Deforestation and Forest Degradation and repealing Regulation (EU) No. 995/2010" (2023), banning the import of timber grown in deforested areas. Such measures impose additional costs on companies operating in the forestry sector, reducing its investment attractiveness.

One of the most famous examples of international regulation is the Soy Moratorium (2024), which was introduced in 2006 to combat illegal deforestation in Brazil. Under this initiative, major agribusiness companies, including Archer Daniels Midland (ADM), Cargill and Bunge, refused to purchase soybeans grown on land that had been cleared by deforestation after July 2008 (ADM Statement on..., 2019; Cargill in the Amazon..., 2019; Amazon soy moratorium, n.d.). ADM, one of the world's largest food corporations, has stated that it does not buy soy from deforested areas of the Amazon and does not make investments in these areas. Similar policies are followed by Cargill and Bunge, which control a significant share of the global soybean market. The refusal of these companies to purchase agricultural products associated with illegal deforestation has contributed to a significant reduction in deforestation in the region. In particular, during the first years of the moratorium, deforestation related to soy production decreased by 84%, and the share of soy grown on land cleared after 2008 fell below 1% of total production in the Amazon (Soy Moratorium, 2024).

In addition to Brazil, similar mechanisms are used in other countries. For example, the EUTR, which prohibits trade in illegally harvested timber (Regulation (EU) No. 995/2010 of the European Parliament and of the Council, 2010). Companies that cannot prove the legality of their products face severe fines and the risk of losing partners. In 2021, France and Germany tightened controls on timber imports, which affected the market for suppliers from countries where illegal logging is common (EU rules against..., n.d.). High regulatory risks and fines are also relevant for Indonesia. In 2021, the country tightened control over timber exports by introducing new measures to combat illegal logging, including the requirement for companies to confirm the legality of their products through the Timber Legality Verification System (SVLK) (Wicaksono, 2021). This has significantly reduced the level of illegal timber trade. As a result, Indonesia has achieved a 70% reduction in illegal logging compared to previous years (Ma'ruf, 2021).

Fines and regulatory restrictions affect not only direct participants in the forest industry, but also international investors. Large financial institutions, such as the World Bank (2024) and the International Monetary Fund (IMF) (n.d.), often require compliance with environmental standards before allocating funds for infrastructure projects. For example, in 2022, the European Investment Bank (2020) refused to finance large-scale logging projects in Southeast Asia due to high environmental risks and insufficient control over illegal logging.

Thus, deforestation has a complex negative impact on the economy of the forestry sector, causing a decrease in the resource base, loss of jobs, lower incomes of local communities, reduced investment, and increased regulatory risks. Companies and countries that fail to implement effective deforestation control mechanisms face severe fines, restricted access to international markets, and loss of investor confidence. This underscores the need to strengthen environmental responsibility and develop more sustainable approaches to forest management.

Effective control over forest resources is a key factor in the fight against illegal logging and forest degradation. Modern monitoring methods allow timely detection of violations, assessment of the scale of losses, and forecasting of possible economic and environmental consequences (Table 1).

Table 1. Methods for monitoring deforestation

Monitoring method	Description	Advantages
Satellite monitoring	Use of satellite images (NASA, ESA) for global monitoring of forest cover changes.	Global coverage, the ability to analyse changes in real time.
Drone technology	Use of drones to detect illegal logging and monitor the state of forest ecosystems.	High accuracy, ability to work in hard-to-reach areas.
GIS analytics	Modelling the effects of deforestation, analysing economic losses and predicting changes in the landscape.	Enables informed decision-making for sustainable forest management.

Source: compiled by the authors based on V. Myroniuk *et al.* (2024)

Thus, modern methods of monitoring deforestation play a crucial role in controlling logging, preventing illegal activities and developing sustainable forest management strategies. The use of satellite technologies, drones and GIS-analytics allows for a timely response to threats, minimising the economic and environmental risks associated with the degradation of forest ecosystems.

The impact of soil erosion in forested areas on the regional economy

Soil erosion in forested regions causes significant economic losses, affecting various sectors of the economy. Firstly, the decline in forest productivity due to erosion leads to a loss of potential for forest regeneration. Eroded soils lose a significant amount of humus, which reduces their fertility and complicates reforestation processes. For example, in the US Midwest, erosion rates average 12.5 tonnes of soil per hectare per year, reaching 250 tonnes in the most problematic cases. This leads to the loss of topsoil, which is rich in organic matter, which negatively affects land productivity. Globally, soil degradation also leads to significant losses of humus. Every year, about 23.7 million tonnes of humus are lost due to erosion, which negatively affects soil bioproductivity (Soil erosion, 2017). The loss of soil fertility leads to a reduction in the productivity of forest plantations, which directly affects the economic stability of regions dependent on the forest industry.

Second, soil erosion leads to increased infrastructure costs due to damage to roads, dams, and buildings caused by landslides. The development of ravines and siltation of water bodies reduce the area of arable land and require additional investment in the restoration and protection of infrastructure. According to research by the University of Central Asia (n.d.) of Environmental Studies, annual nutrient losses due to erosion in Kazakhstan and Uzbekistan are up to 700,000 tonnes of nitrogen compounds, 320,000 tonnes of phosphate fertilisers and 250,000 tonnes of potassium salts. This is equivalent to the loss of the ability to grow more than 900,000 tonnes of grain crops annually, which significantly affects the region's food security.

Third, erosion worsens the water regime, reducing the quality of water resources. For example, siltation of reservoirs due to erosion processes globally reduces the water capacity of reservoirs by 1%-2% annually, which significantly affects water supply and increases the cost of water treatment. This phenomenon is particularly acute in China, India and sub-Saharan Africa (Nigeria and Kenya). In China, particularly in the Huang He River basin, soil erosion has caused sediment to accumulate in reservoirs, reducing their capacity and increasing the risk of a water crisis. In India, the siltation of the Ganges and Brahmaputra rivers is limiting water supplies for agriculture and the energy sector, forcing the government to invest heavily in dredging. In the Sahelian region of Africa, intensive erosion has caused degradation of water bodies, making it difficult for industrial and agricultural facilities to access water, which negatively affects economic development (Soloviy, 2016).

Soil erosion causes significant losses to agriculture, especially through wind erosion, which damages spring sprouts of crops such as sugar beet, sunflower, and corn. Wind erosion results in the loss of up to 24 billion tonnes of topsoil globally each year, which has a significant impact on yields. In arid regions such as Central Asia (Kazakhstan, Turkmenistan), soil blowing can destroy up to 25% of crops, forcing farmers to spend additional money on reseeding and protecting their fields (Food and Agriculture Organization of the United Nations, n.d.).

Thus, soil erosion in forested regions has a complex negative impact on the economy, requiring the implementation of effective measures to prevent and minimise its consequences. Soil erosion monitoring in forest regions is an important tool for assessing its effects and developing strategies to combat land degradation. Modern technologies make it possible to track changes in soil cover, analyse the level of siltation of water bodies and predict further changes in the landscape. Table 2 shows the main methods of erosion monitoring.

Table 2. Methods monitoring soil erosion

Monitoring method	Description	Advantages
Radar images of satellites	Recording changes in land cover using satellite technology.	Allows tracking erosion over large areas in real time.
Hydrological analysis	Assessment of the level of siltation of rivers and other water bodies to determine the impact of erosion.	It helps to determine the degree of water pollution and flooding risks.
Modelling of landscape changes	Predicting future changes in relief and assessing possible economic consequences.	It helps to develop strategies to combat erosion and restore degraded land.

Source: compiled by the authors based on European Space Agency (2023)

The use of these methods allows identifying erosion risks in a timely manner and taking appropriate measures to minimise them. The introduction of satellite monitoring, hydrological analysis and digital modelling of landscape changes helps to preserve forest ecosystems and protect natural resources.

The impact of biodiversity changes on the economics of the forest sector

Biodiversity loss has long-term economic consequences for regions where forestry plays an important role. The loss of species diversity disrupts the ecological balance, leading to a decrease in the productivity of forest ecosystems, reduced economic opportunities and increased costs of forest management. The decline in ecosystem services has a significant impact on economic processes, as forests perform a natural function of climate regulation, air and water purification, soil conservation and nutrient cycling. For example, in the tropical Amazon region, the loss of forest area has reduced the region’s ability to retain moisture, leading to more frequent droughts and a negative impact on agriculture (de Sousa *et al.,* 2016). The decline in these services leads to an increase in public spending on ecosystem restoration and climate change mitigation measures.

Losses for the pharmaceutical and food industries are associated with the disappearance of rare plant species with high economic value. According to the World Health Organization (2013), about 80% of the world's population uses medicinal plants to treat various diseases, and many of these plants grow in forests. The disappearance of rare species, such as the African yohimbe or the South American lapacho, leads to a reduction in potential resources for the production of new medicines. In addition, forest degradation reduces the diversity of wild fruits, nuts and honey plants, which is detrimental to the food industry.

The decline in tourist attraction is another significant economic impact of biodiversity loss. Forest ecosystems attract millions of tourists who visit national parks, nature reserves and recreational areas. For example, in 2023, the global ecotourism market was estimated to be worth USD 191.3 billion, and its growth is directly dependent on the preservation of the natural environment. In countries where forests are degrading, such as Brazil and Indonesia, due to the disappearance of species, there is an outflow of tourists, which leads to economic losses for local communities and tourism-related businesses (Ecotourism Market Size…, 2024).

Reducing the resilience of forest ecosystems makes them more vulnerable to diseases and pests, which leads to additional costs for pest control and forest fires. In 2020, the Czech Republic, Germany, and Austria suffered the largest losses due to bark beetles. In the Czech Republic, a large-scale epidemic led to an oversupply of timber, which reduced its value and forestry companies' revenues. In Germany, the drying out of spruce forests led to a sharp increase in emergency logging, a glut of timber on the market, and financial losses for companies. In Austria, significant damage to forests, especially in the Alps, led to a decline in production in the woodworking industry and job losses. In general, the bark beetle epidemics in these countries have led to lower timber prices, higher costs of sanitary felling, and economic losses for the forestry sector (Food and Agriculture Organisation of the United Nations, n.d.). This has led to significant economic losses in the forestry sector and the need to allocate additional funds for sanitary felling and forest restoration. Thus, biodiversity loss leads to significant economic losses affecting various industries, from forestry and pharmaceuticals to tourism and agriculture. Biodiversity loss and climate change pose significant economic risks, especially in sectors such as agriculture and infrastructure. Climate change is leading to an increase in average annual temperatures and uneven distribution of precipitation, which negatively affects yields. For example, in the United States, particularly in North Dakota, farmers are facing the need to adapt crop rotations and production systems due to changing climate conditions. This requires additional investment in new technologies and practices, which increases production costs (Hughes, 2024).

Extreme weather events, such as floods and heat waves, cause damage to infrastructure, resulting in significant costs to rebuild. In the United States, for example, floods and extreme heat accelerate the deterioration of bridges, many of which were built decades ago and were not designed to withstand modern climate stresses. This poses a safety hazard and requires significant financial resources for repair and modernisation (Hughes, 2024). In general, the combination of biodiversity loss and climate change increases economic risks, in particular through reduced agricultural productivity and increased costs for infrastructure maintenance and restoration. This requires the implementation of effective forest management strategies and biodiversity conservation as a key factor in economic stability. To effectively monitor the state of biodiversity, modern methods are used to assess changes in wildlife populations, soil microflora, and species composition of forest ecosystems (Table 3).

Table 3. General characteristics of test areas

Monitoring method	Description	Advantages
Automatic camera traps	Use of cameras with motion sensors to monitor wildlife populations in the natural environment.	Provides accurate data on species abundance and behaviour without human intervention.
DNA analysis from soil samples	Determining changes in the microflora and composition of soil organisms by analysing soil samples.	It helps to identify species, including rare and endangered species, without the need for direct observation.
Indices biodiversity	Quantification of changes in the species composition of flora and fauna using special indices (e.g., Shannon index, Simpson index).	Provides a comprehensive analysis of biodiversity dynamics and helps to predict environmental changes.

Source: compiled by the authors based on A.F. O'Connell *et al.* (2011)

These methods help to identify threats to biodiversity, analyse environmental trends and develop strategies for the conservation of natural ecosystems. Automated camera traps provide continuous monitoring of animal populations, helping to combat poaching and evaluate the effectiveness of conservation measures.

Economic consequences of forest degradation for regional development

The degradation of forest landscapes has serious economic implications for regional development, as it affects employment, financial flows, the investment climate and demographic processes. The loss of forests not only reduces economic activity in the logging sector, but also affects related industries such as construction, woodworking, agriculture, and tourism. Reduced budget revenues are one of the most visible consequences of forest degradation. Logging companies and woodworking enterprises generate a significant share of tax revenues for local budgets. For example, in Canada, the forestry industry provides more than USD 12 billion in tax payments annually, but due to the reduction in forest area and restrictions on logging, this figure may decrease (Natural Resources Canada & Canadian Forest Service, 2020). A similar situation is observed in Southeast Asian countries, where illegal logging leads to the shadow economy and a reduction in official budget revenues (Food and Agriculture Organization of the United Nations, n.d.).

Successful and problematic reforestation projects in different countries demonstrate the importance of a comprehensive approach and consideration of local conditions.

In Indonesia, Eden Reforestation Projects launched a large-scale mangrove restoration initiative in 2017 on the island of Biak in Papua province. During the first year, more than 1.7 million trees were planted, and as of November 2020, more than 22 million trees were planted in 10 project locations. This success highlights the importance of collaboration between international organisations and local communities to achieve sustainable results in forest restoration (Eden Reforestation Projects plants..., 2020).

In Brazil, in December 2024, a plan was announced to restore 40 million hectares of degraded rangeland through commercial reforestation, including eucalyptus plantations. While this may contribute to economic development and carbon sequestration, critics have raised concerns about the impact of eucalyptus monocultures on biodiversity and water resources. This example demonstrates the difficulty of balancing economic interests with environmental sustainability in forest restoration projects (Hillsdon, 2024).

In countries heavily affected by deforestation, such as Indonesia and Brazil, governments are forced to spend billions of dollars on greening and protecting natural landscapes. Indonesia has introduced a moratorium on deforestation of old-growth forests and peatlands, and is reviewing plantation licences. Deforestation rates have decreased, but illegal logging remains a problem (Soloviy, 2016). Brazil plans to restore 40 million hectares of grassland through eucalyptus plantations, which is controversial due to possible negative impacts on biodiversity and water resources (Hillsdon, 2024).

Demographic changes are a consequence of the decline in economic activity in regions affected by forest degradation. Job losses in the forestry industry, wood processing and related sectors lead to population migration. In Latin America, deforestation combined with climate change is creating conditions that are forcing people from forested regions to seek employment in urban areas. For example, in Brazil, the loss of jobs in the forestry industry led to the migration of about 15% of the population from rural Amazonian regions in 2015-2020 (World Bank, 2024).

Declining land and property values are another long-term consequence of forest degradation. Areas that have lost forests become less attractive to investors as they lose their environmental and recreational benefits. In the United States and Canada, the market value of deforested land can fall by 30-50%, especially if it has become prone to erosion or has lost its economic value. In countries where forested areas are of tourist value, such as Switzerland or Finland, landscape degradation can reduce the flow of tourists and, consequently, the region's income (Food and Agriculture Organization of the United Nations, n.d.). Thus, the economic consequences of forest landscape degradation go far beyond the forest sector. They affect tax revenues, necessitate additional environmental expenditures, cause demographic changes, and lead to a decline in land and property values. This calls for an integrated approach to natural resource management, including sustainable forest management, investment in ecosystem restoration and the creation of alternative economic opportunities for regions dependent on the forest sector.

The degradation of forest landscapes is the result of not only environmental but also socio-economic factors that largely determine the extent of deforestation and the rate of depletion of forest resources (Shuplat *et al*., 2022). One of the key factors is corruption in the forestry sector, which facilitates illegal logging and export of products without proper control. The absence of effective monitoring allows business entities to circumvent restrictions, manipulate reporting and exploit forest resources beyond the established environmental standards. This creates a shadow timber market, which undermines the economic stability of the forestry sector and complicates its regulation at the state level (Key corruption risks…, 2025).

Economic pressure caused by the growing demand for wood in the construction, industrial, and energy sectors has a significant impact on deforestation. Infrastructure development, production of paper, furniture, and biofuels stimulate an increase in timber harvesting, which poses risks to forest ecosystems. This is especially true in countries where forestry is a strategic sector of the economy and legislative regulation remains weak. In Ukraine, the partial lifting of the moratorium on timber exports has led to increased timber harvesting, which has exacerbated the problem of deforestation and increased economic risks for the timber processing industry (Yaroshchuk, 2018; Turchyn, 2024).

Social factors also play an important role in forest degradation. In regions where forestry is the main source of employment, the population is dependent on timber harvesting, making it difficult to implement restrictions and environmental restoration programmes.

Low awareness of the long-term consequences of deforestation and the lack of alternative sources of income force local communities to maintain intensive use of forest resources. In such circumstances, insufficient funding for environmental programmes and the lack of effective government support mechanisms only exacerbates the problem. In view of the above, a comprehensive approach to regulating the industry is needed to reduce socio-economic pressure on forest resources. This includes strengthening control over logging, eliminating corruption schemes, creating economic incentives for the development of alternative materials and technologies, and supporting local communities through sustainable development and ecotourism programmes. Only a systematic approach will reduce the negative impact of anthropogenic factors and ensure a balance between economic interests and the preservation of forest ecosystems.

Ways to reduce economic risks associated with forest degradation

Reducing economic risks caused by forest landscape degradation requires a comprehensive approach that includes a sustainable approach to forest management, effective economic mechanisms and innovative technological solutions. One of the key ways to minimise economic risks is Forest Stewardship Council International (n.d.) certification, which guarantees that timber harvesting meets environmental and social standards. The introduction of this certification allows controlling logging, ensuring the rational use of resources and reducing illegal logging. In EU countries, where more than 50% of commercial timber is certified by FSC, this approach helps to increase investment in the sustainable development of the forestry sector.

Another method is agroforestry, which involves planting trees to combat soil erosion. Combining agriculture with forest plantations not only protects soil but also improves yields. For example, in China, a large-scale greening programme called the Great Green Wall has helped to stop the expansion of deserts and increase the productivity of agricultural land (Hillsdon, 2024). In addition, the development of renewable sources of income, such as ecotourism and recreational areas, contributes to economic growth without harming forests. In Sweden and Canada, forest parks and protected areas generate millions of dollars in revenue each year, supporting local communities and promoting conservation. In Sweden, national parks and nature reserves generate significant ecotourism revenues, funded by the state and the private sector. Investments are directed to the development of infrastructure, eco-camps, and tourist routes (Swedish Environmental Protection..., n.d.). In Government of British Columbia (n.d), two funds of CAD 60 million each have been created to support ecotourism and forest conservation. The projects are funded by the government and private donors, which ensures sustainable development and protection of forest ecosystems. An effective way to regulate deforestation is through environmental taxation, which involves imposing taxes on logging and timber use. In a number of countries, such as Finland and Norway, the introduction of environmental taxes has helped to reduce deforestation and stimulate the use of recycled raw materials (Yegorova, 2015).

Another important mechanism is the financing of forest restoration through government and international subsidies. For example, in Germany, government support for the Forest Ecosystems programme allowed for the planting of more than 30 million trees in 2014-2024, which significantly improved forest health and helped reduce soil erosion (Walcott *et al.*, 2022). At the international level, the GCF is a key donor supporting climate initiatives, including reforestation projects. In 2023, the GCF approved

USD 2.1 billion in funding for 34 new projects, expanding its portfolio to USD 13.5 billion (Green Climate Fund Board…, 2021).

Another promising area is carbon credit mechanisms, which involve the sale of certificates for forest conservation. This mechanism allows companies to offset their CO_2 emissions by investing in reforestation projects. For example, Brazil and Indonesia have raised hundreds of millions of dollars through the carbon credit market, which has helped reduce deforestation in these countries (World Bank, 2024).

Innovative technologies also play a key role in forest conservation. The use of drones for monitoring allows for real-time tracking of deforestation, detection of illegal logging, and assessment of the state of forest ecosystems. In Costa Rica, where drones are used to monitor logging, the level of illegal logging has decreased by 35% (World Bank, 2024). Another innovation is the introduction of artificial intelligence for risk prediction, which allows analysing satellite data and identifying areas at risk of deforestation. In the United States, such a system is used to assess the impact of climate change on forests, which allows for timely development of adaptation strategies (National Integracy Fire Center, 2025).

Reducing dependence on wood is also possible through the development of alternative materials, such as biodegradable polymers, recycled composites, and bamboo. For example, Japan is actively using innovative materials based on mushroom mycelium and agricultural waste to replace wood in construction and packaging (Alaneme *et al.,* 2023). The introduction of a sustainable approach to forest management, financial mechanisms to stimulate forest conservation, and innovative technologies are key ways to minimise economic risks associated with forest landscape degradation. Effective monitoring, the development of environmental entrepreneurship, and international cooperation will help preserve forest resources and ensure the economic stability of regions that depend on the forest sector. To assess possible ways of developing the forestry sector, it is advisable to consider three main scenarios: pessimistic, basic and optimistic. They demonstrate different approaches to forest management and their possible economic consequences (Table 4).

Table 4. Forecast scenarios for the forestry sector

Scenario	Main characteristics	Consequences	Examples of countries
Pessimistic	Lack of effective control, increased illegal logging, weak environmental policy, low level of investment in reforestation.	Reduced forest resources, loss of biodiversity, soil erosion, reduced productivity of the forest industry, economic losses and reduced employment.	Liberia, Democratic Republic of Congo, Bolivia – high rates of deforestation, weak control, lack of sustainable forest management programmes.
Basic	Maintaining the current forest management policy without significant reforms, partial reforestation, limited control over deforestation.	Moderate reduction in forest area, increase in timber prices, risks for the timber industry, partial compensation for losses through restoration programmes.	Ukraine, Brazil, Indonesia — environmental legislation is in place, but control remains insufficient, and partial reforestation is underway.
Optimistic	Introduction of strict controls, digital forest monitoring, expansion of FSC certification, development of ecotourism and alternative sectors.	Stabilisation of forest resources, sustainable economic growth, creation of new jobs, reduction of regional dependence on logging, improvement of the environmental situation.	Finland, Sweden, Germany – developed sustainable forest management systems, FSC certification, digital monitoring of forest resources.

Source: compiled by the authors

The presented scenarios allow assessing the long-term consequences of different management strategies. It is evident that a passive approach to management (pessimistic scenario) causes significant environmental and economic risks, while the baseline scenario only partially compensates for the negative impacts. The optimistic scenario, which envisages the implementation of strict control measures, the development of sustainable forest management models and support for local communities, is the most promising option for ensuring economic stability and conservation of natural resources.

Discussion

The results of the study demonstrated a significant impact of forest landscape degradation on the economic stability of regions, which is consistent with the findings of other studies. The work of K. Navare *et al.* (2021) emphasised the importance of integrating circular economy principles for biological cycles, which helps to reduce economic losses caused by deforestation. The use of regulatory mechanisms, such as FSC certification, is confirmed by the above guidelines for stabilising economic losses in the forest sector. The study by H. Kassa *et al.* (2022) demonstrated that the restoration of forest landscapes in Ethiopia through the implementation of large-scale programmes helped to reduce soil erosion and economic risks. Successful examples of regional greening programmes confirm the effectiveness of such initiatives, such as those justified in the study.

The analysis presented by S. Eshetu *et al.* (2024) indicates the effectiveness of monitoring erosion processes and the introduction of the latest technologies for landscape restoration. The data obtained on economic losses due to soil erosion are in line with the results of the study, which showed significant losses in agriculture due to wind erosion. The monitoring of land degradation in Central Asia, highlighted by L. Jiang *et al.* (2022), in demonstrated the effectiveness of using geographic information technologies to track changes in landscapes. The use of such technologies supports the conclusions about the importance of GIS monitoring for assessing the economic impact of forest degradation.

The results confirm the importance of monitoring forest landscape degradation for the economic stability of regions. The study by H. Bo *et al.* (2023) focuses on the classification of agricultural land productivity degradation, which makes it possible to assess the impact on the economy and identify areas for intervention. The use of integrated monitoring approaches, such as land use change analysis, allows not only to record the level of degradation but also to identify the main causes of this process (Skydan *et al.*, 2021). This approach facilitates the development of targeted strategies aimed at reducing economic losses by adapting land use to changing environmental conditions. This confirms the expediency of a systematic approach to monitoring, which allows predicting the long-term effects of degradation and taking timely measures to mitigate them.

The practice of tropical forest restoration described by Y. Indrajaya *et al.* (2022), demonstrates a significant positive effect from the implementation of restoration programmes. The use of modern technologies and a scientifically based approach to forest restoration contributes to increasing the resilience of ecosystems to the impact of erosion processes. Reducing erosion as a result of such measures is closely linked to reducing economic risks arising from soil loss, reduced yields and increased costs of restoration (Pichura *et al.*, 2023). In addition, such programmes support the socio-economic development of regions by providing additional sources of income for local communities and creating new opportunities for attracting investment in sustainable forestry. The effectiveness of such initiatives confirms the need for their further implementation and scaling up.

The results of T. Fremout *et al.* (2021) show the importance of a properly selected tree species composition to ensure the sustainability of forest landscapes in changing climatic conditions. The use of biodiversity as a basis for restoration measures shows high efficiency in terms of long-term economic benefits. In the work of R.K. Mishra & R. Agarwal (2024), the authors substantiated a sustainable approach to the management of degraded areas, which includes a combination of environmental and economic instruments. The application of such approaches provides comprehensive support for restoration processes. The study by W. Shao *et al*. (2024) proposes an improved model for assessing land degradation, which allows for a more accurate determination of the scale of the problem and its impact on the economy. The use of integrated models helps to improve the efficiency of decision-making on the management of degraded areas.

The results of the analysis confirmed the significant impact of forest landscape degradation on environmental sustainability and economic development of regions, which is consistent with the findings of S. Shah & D. Race (2024). The study emphasises the importance of Reducing Emissions from Deforestation and Forest Degradation (REDD+) programmes as an effective tool to combat deforestation. These programmes help to reduce greenhouse gas emissions by implementing measures for forest conservation, restoration and sustainable management of forest resources. The application of such mechanisms in regions with high deforestation rates provides a comprehensive impact on the environmental and economic situation, reducing the risks of ecosystem degradation. The study also points out the importance of involving local communities and international support, which allows for effective implementation of programmes and improves their effectiveness. The effectiveness of REDD+ confirms the need for further development of such initiatives to maintain environmental sustainability and reduce economic risks associated with forest landscape degradation.

The study by Z. Du *et al.* (2024) found that the dynamics of land use change in the steppe regions of Eurasia directly affects the extent of land degradation. These results confirm the conclusions about the need for a systematic approach to landscape management to reduce negative economic consequences. The analysis of U. Khujanazarov *et al.* (2024) demonstrated the effectiveness of monitoring the dynamic state of the vegetation cover of pastures in the Kashkadarya basin. The results confirm the feasibility of using integrated monitoring approaches to ensure sustainable landscape management, similar to those proposed in the data presented here.

M.R. Saoum & S.K. Sarkar (2024) drew attention to changes in mangrove forests and their impact on the environment. The estimation of economic losses due to the degradation of mangrove ecosystems correlates with the conclusions about the economic consequences of forest landscape degradation in coastal regions. Y.H. Khachoo *et al.* (2024) emphasised the economic consequences of changes in land use and land cover, which also includes a reduction in carbon stocks. The use of Google Earth Engine for the analysis confirms the effectiveness of the latest technologies in studying such changes, which is consistent with the results obtained. S. Kumi *et al.* (2024) identified barriers and opportunities in restoring degraded forest landscapes in Ghana. The analysis confirmed that the successful implementation of restoration programmes requires taking into account socio-economic factors, which coincides with the conclusions about the need for an integrated approach to solving degradation problems.

The study by S. Bayraktar *et al.* (2024) examined the directions of land degradation within the Istanbul metropolitan area, covering four decades. The results indicate a significant impact of urbanisation and land use changes on the state of land resources. The assessment of the dynamics of degradation underlines the importance of long-term monitoring, which allows not only to identify the main factors of degradation, but also to predict its consequences for the economic development of regions (Adamenko *et al*., 2023). This confirms the need to integrate monitoring into spatial planning processes to reduce the negative impact of degradation on ecosystem services and the economy.

The evaluation of the research results emphasises the importance of integrated approaches to managing degraded landscapes. Taking into account environmental, economic and social aspects provides a comprehensive understanding of the scale of the problem and allows for the development of targeted strategies to reduce economic risks. This approach contributes to the effective restoration of forest and land resources, which is of particular importance for regions with different natural conditions and the degree of anthropogenic impact. The use of modern technologies and monitoring models helps to improve the efficiency of management decision-making and ensure the resilience of landscapes to negative factors.

Conclusions

The study showed that the degradation of forest landscapes has a complex impact on the economy of regions where the forest sector plays a key role. It was found that the annual loss of forest cover in the world reaches 10 million hectares, which leads to a decrease in the resource base of wood, an increase in its cost and a reduction in the production capacity of the woodworking industry. In Southeast Asia and Latin America, this has resulted in a 15-25% reduction in employment in the forestry sector and a decrease in tax revenues to local budgets.

Estimates of economic losses have shown that illegal logging causes annual losses of USD 5-7 billion in Latin America and USD 3-4 billion in Africa. At the same time, in countries with developed FSC certification mechanisms, illegal logging does not exceed 5% of total logging, which ensures the stability of the industry and attracts investment. An analysis of international regulatory measures (EUTR, Amazon Soy Moratorium) has shown that strengthening control over forest management helps to reduce deforestation and increase the market sustainability of forest products.

Erosion processes in forested regions have been found to worsen soil fertility, making reforestation more difficult. For example, in Kazakhstan and Uzbekistan, annual nutrient losses due to erosion lead to a decrease in agricultural land productivity, which poses a threat to food security. In addition, siltation of reservoirs increases water and energy costs by 1-2% annually.

The decline in biodiversity in forest ecosystems reduces their resistance to pests and diseases, causing losses to wood processing companies. For example, in the Czech Republic and Germany, large-scale bark beetle epidemics have led to an oversupply of timber, which has reduced its value and reduced the profits of forestry companies. In addition, the decline in biodiversity has a negative impact on the tourist attractiveness of the regions, which affects the income of local communities.

To mitigate the economic risks caused by forest degradation, it is necessary to strengthen control over illegal logging, expand the FSC certification system and develop alternative revenue streams such as ecotourism. Encouraging investment in forest monitoring technologies, including satellite imagery, drones and GIS analysis, is also important. A promising area is the development of carbon credits, which would allow for the attraction of funding for forest conservation.

Further research should focus on assessing the effectiveness of innovative forest management methods and analysing the impact of climate change on reforestation dynamics. In addition, it is necessary to expand the empirical base on the economic consequences of forest degradation in Central Asia, which will allow for more accurate risk forecasting and the development of adaptive strategies for managing forest landscapes.

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Conflict of Interest

None.

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Моніторинг економічних ризиків, пов’язаних з деградацією лісових ландшафтів

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Анотація. Метою дослідження було оцінити економічні ризики, спричинені деградацією лісових ландшафтів, та їх вплив на економіку лісового сектору і регіональний розвиток. В ході аналізу було проаналізовано вплив вирубки лісів, ерозії ґрунтів, втрати біорізноманіття та зміни клімату на стійкість лісового господарства, ринок праці, інвестиційну привабливість та фінансові потоки в регіонах. Використано комплексний підхід, що включає статистичний аналіз даних, порівняльну оцінку змін у лісовій галузі та прогнозування можливих економічних наслідків за різними сценаріями розвитку подій. Дослідження показало, що в період з 2015 по 2024 рік глобальна втрата лісового покриву сягала 10 мільйонів гектарів щорічно, що призводило до скорочення запасів деревини та зростання цін на неї на 15-25 % у найбільш постраждалих регіонах. Зменшення площі лісів безпосередньо вплинуло на зайнятість у лісовій галузі, спричинивши скорочення робочих місць у секторі на 20-30 % у Південно-Східній Азії та Латинській Америці, де лісозаготівля є важливим джерелом доходу. Результати показують, що скорочення податкових надходжень від лісової галузі та зменшення місцевих бюджетів призвели до обмеження фінансування соціальних програм та інфраструктурних проектів у сільській місцевості. Аналіз також показав, що нелегальна вирубка лісів залишається серйозною проблемою, оскільки до 30 % світового ринку деревини може мати нелегальне походження, що підриває економічну стабільність галузі та ускладнює міжнародне регулювання. Втрата біорізноманіття та ерозія ґрунтів призвели до збільшення витрат на екологічне відновлення лісових територій, які в деяких країнах перевищили 5 мільярдів доларів США. Запропоновано комплексні заходи для зниження економічних ризиків, серед яких запровадження жорстких регуляторних механізмів, розвиток FSC-сертифікації, стимулювання інвестицій у відновлення лісів, впровадження цифрових технологій моніторингу, зокрема супутникового спостереження та використання дронів. Результати дослідження можуть сприяти розробці стратегій управління лісовим господарством, екологічного контролю, зниження економічних ризиків, впровадження технологій моніторингу та оцінки впливу деградації лісів на регіональний розвиток

Ключові слова: довкілля; сталий розвиток; екосистема; ерозія; біорізноманіття

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Ecological role of tree and shrub plantations in urban landscapes

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Abstract. The study aimed to determine the impact of green spaces on the environmental sustainability of cities and to identify the most effective methods of greening. The study analysed the impact of different types of tree and shrub plants on reducing the level of pollutants, including particulate matter (PM2.5 and PM10) and carbon dioxide, as well as their ability to regulate temperature and create comfortable climatic conditions. The results demonstrated that the most

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effective plant species for urban landscaping were black poplar, which had the highest particulate matter filtration capacity (9.8 g/m^2/year PM2.5 and PM10) and high CO_2 uptake (24 kg/tree/year), Tatar maple, which provided significant air pollution reduction (7.5 g/m^2/year PM2.5 and PM10) and CO_2 capture (18 kg/tree/year), common pine, which showed high efficiency in particulate matter reduction (8.7 g/m^2/year PM2.5 and PM10) and carbon dioxide uptake (22 kg/tree/year), and Tien Shan spruce, which combined air cleaning ability (7.9 g/m^2/year PM2.5 and PM10) with high CO_2 uptake (21 kg/tree/year). These plant species demonstrate a high ability to absorb pollutants and reduce air temperature by 3.2-4.5°C in summer. In Kyrgyzstan, the area of green spaces in cities is 12% of the total area, which is significantly lower than in developed countries such as Singapore (47%), Germany (40%, Canada (38%) and Sweden (44%). In Bishkek, the capital of Kyrgyzstan, there are 9 m^2 of green spaces per inhabitant, while in Singapore this figure reaches 50 m^2 and in Germany 38 m^2. Analyses of international experience revealed that developed countries actively applied innovative landscaping methods. Singapore made extensive use of vertical gardens and water-saving technologies, Germany prioritised the regeneration of natural areas and the creation of eco-parks, Canada implemented integrated forest protection programmes, and Sweden introduced adaptive landscaping and sustainable forest planting. These measures contributed to significant improvements in the environmental sustainability of urban environments. The findings of the study emphasise the need for an integrated approach to urban greening in Kyrgyzstan, based on the selection of the most sustainable tree and shrub species, as well as the introduction of modern greening technologies

Keywords: sustainable development; green infrastructure; climate adaptation; biodiversity; urban greening

Introduction

The research relevance is determined by the increasing urbanisation and deterioration of the environmental situation in cities, which leads to significant air pollution, temperature increase and decrease in biodiversity. With climate change and increasing building density, green spaces are becoming one of the key tools for creating a sustainable and comfortable urban environment. Woody and shrubby plants not only improve air quality by absorbing carbon dioxide (CO_2) and filtering particulate matter (PM2.5 and PM10) but also contribute to reducing the heat island effect and increasing urban adaptation to changing climatic conditions. The problems of the study are related to the insufficient area of green spaces in cities, the lack of a systematic approach to their placement and the lack of data on the most effective plant species for improving the ecological situation. Kyrgyzstan was chosen for the analysis due to its low level of urban green space, significant air pollution, heat island effect and the need to adapt the international experience to improve environmental sustainability. In Kyrgyzstan, there was a decrease in green spaces, which increased the problems of air pollution and overheating in the urban environment, while in Germany, Canada, Sweden and Singapore, programmes to expand green areas and integrate green solutions into urban infrastructure were actively developed. The comparative analysis of international experience identified the best practices of green space management and adapt them to the conditions of Kyrgyzstan, which can contribute to improving the quality of life and sustainable urban development.

As shown by R. Absatarov *et al.* (2024), significant changes in the composition of tree and shrub plantations were observed in the southern regions of Kyrgyzstan, which influenced the local climate and biodiversity. The study confirmed the importance of preserving natural representatives of the genus *Salix* L. under increasing anthropogenic pressure. According to K. Mehta *et al.* (2021), the condition of floodplain ecosystems in the highlands of Kyrgyzstan was closely related to the level of energy consumption of the local population. The authors noted that the degradation of green spaces in these regions exacerbated the problems of microclimate change, which required the development of comprehensive measures for their restoration. As noted by S. Missall *et al.* (2022), the use of floodplain forests in Central Asia, particularly in the Naryn region of Kyrgyzstan, affected the ecological balance and sustainability of forest ecosystems. The authors emphasised that rational management of these areas could contribute to water conservation and climate change mitigation. A study by H. Cohen *et al.* (2021) confirmed that tree and shrub plant diversity is directly related to the abundance of urban pollinators, which are crucial for maintaining biodiversity.

According to N. Zhang *et al*. (2022), the aesthetic perception of green spaces affects the quality of life of the population by reducing stress levels and increasing the social activity of urban dwellers. Furthermore, S.K. Braman & B. Griffin (2022) determined that the expansion of urban green spaces and the use of flowering shrubs promotes the maintenance of insect pollinator populations, which is critical for maintaining ecosystem connectivity. As shown by M.G. Mitchell & T. Devisscher (2022) the level of urbanisation has a significant impact on landscape structure and the functionality of ecosystem services provided by urban forests. The study concluded that high building density reduces the biological productivity of green spaces, which in turn reduces their ability to mitigate the negative effects of urbanisation.

According to K. Isinkaralar (2024), trees in urban environments can be used as natural biomonitors to determine the level of air pollution by heavy metals. This monitoring method improved the accuracy of technogenic emissions impact assessment on urban ecosystems and allowed to identification of areas with the highest concentration of pollutants. As shown by M. Mngadi *et al.* (2022) remote sensing methods and the use of biophysical parameters assessed the primary productivity of tree plantations in urban environments. The results confirmed that restored green spaces have a significant potential for carbon sequestration and, therefore substantial for climate change mitigation.

As concluded by J.D. Karimi *et al.* (2021a), the spatial configuration of urban green spaces is substantial in the distribution of ecosystem services. The study demonstrated that uniform and cohesive placement of plantings contributes to more effective temperature reduction and air purification, compared to dispersed green spaces. According to N. Hosseinpour *et al.* (2022), the integration of urban agriculture into park spaces can significantly enhance their ecological and social value. The study identified that such initiatives not only increase green spaces but also involve the local population in maintaining and developing green infrastructure. Lastly, S. Yilmaz *et al.* (2022) revealed that different urban development patterns significantly affect air pollution levels and thermal comfort. The study demonstrated that areas with a high density of greenery have better air quality and thermoregulation compared to areas with little or no green space. The research confirms that green spaces are central to the reduction of air pollution, mitigating the effects of urbanisation and improving the microclimate of cities.

The study aimed to assess the impact of green spaces on urban ecology and compare Kyrgyzstan's greening strategies with international experience. The study objectives included assessing the effectiveness of tree and shrub plantations in reducing air pollution and regulating the microclimate, as well as a comparative analysis of the greening strategies of Kyrgyzstan, Singapore, Germany, Canada and Sweden.

Materials and Methods

The study analysed black poplar (*Populus nigra*), Tatar maple (*Acer tataricum*), small-leaved linden (*Tilia cordata*), birch (*Betula pendula*), common pine (*Pinus sylvestris*), Tien Shan spruce (*Picea schrenkiana*), honeysuckle (*Lonicera*) and cotoneaster (*Cotoneaster*), accounting for their impact on air quality, microclimate regulation and biodiversity maintenance. The information base was based on official statistical data reflecting the current state of green areas in Bishkek, Osh, Karakol and Tokmak for 2016-2024, including the number and species diversity of tree and shrub plantations, their spatial distribution and impact on environmental parameters (Orlova, 2023; Green City Action..., 2024). Statistical methods were used to analyse the data by assessing the significance of differences and correlation analysis. In particular, Student's t-test was used to compare the mean values of environmental parameters in greened and non-greened areas, Mann-Whitney U-test to test differences in the distribution of numerical indicators between groups of countries, Fisher's criterion to assess the relationship between the level of greening and the decrease in air temperature, and Pearson's correlation analysis to determine the degree of relationship between the density of green spaces and the level of air pollution. The data collected assessed the degree of effectiveness of green spaces in reducing air pollution, their ability to absorb carbon dioxide (CO_2), filter particulate matter (PM2.5 and PM10), and their role in maintaining and enhancing biodiversity in urban environments. The performance of tree and shrub plantations was assessed using a 5-point scale, where 5 points for plants with maximum performance in all parameters, 4 points with high but not maximum, 3 points with average values, 2 points with low performance, and 1 point with minimal contribution.

Additionally, data from international organisations including the United Nations Environment Programme (2023), the Food and Agriculture Organisation of the United Nations (2025), and government agencies in Germany (Blecken *et al.*, 2025), Canada (Canada's climate plans..., 2023), Sweden (Biosphere reserves for..., n.d.) and Singapore (National Environment Agency, 2025) responsible for environmental planning and urban green space management were used. The programmes of Germany, Canada, Sweden and Singapore were chosen because these countries demonstrate different effective approaches to greening: Germany's natural area regeneration, Canada's forest protection, Sweden's adaptive landscaping, Singapore's vertical gardens and water conservation. Their government agencies are developing strategies that improve the environmental sustainability of cities, which makes their experience valuable for Kyrgyzstan. The choice of Singapore, Germany, Canada and Sweden is since these countries, despite different climatic conditions, effectively adapt landscaping to urban space. Canada and Sweden implement sustainable forest plantations in cool climates, Singapore develops vertical greening and water conservation in tropical climates, and Germany uses eco-parks and restoration of natural areas in temperate zones. This identified key differences in approaches to green space development and management, identified factors influencing the effectiveness of green spaces, and assessed potential opportunities for adapting successful strategies in the Kyrgyz context.

The methodological part of the study was based on statistical analysis and quantitative data processing methods. To assess the effectiveness of tree and shrub plantations in reducing air pollution in 2024, indicators of carbon sequestration (CO_2), the degree of particulate matter capture and filtration of gaseous pollutants were used. The effectiveness of tree and shrub plantations in supporting biodiversity was assessed by the number of species living in green areas, species diversity index and availability of food resources for birds and pollinators. For this purpose, data on the number and species composition of plants, their resistance to adverse factors of the urban environment, as well as their role in creating favourable conditions for birds, insect pollinators and other representatives of urban fauna were analysed. The method of comparative analysis was used to identify the most effective plant species recommended for wide use in urban landscaping. The study included calculations of the average air purification capacity of different species of woody and shrubby plants, as well as their contribution to the formation of ecologically sustainable urbanised ecosystems. Calculation of pollutant uptake by plants was performed according to formula (1):

$$A = C \times V \times T, \qquad (1)$$

where A – total volume of absorbed pollutants (g/m^2); C – average concentration of pollutants (g/m^3); V – volume of air passing through the vegetation (m^3); T – measurement time (h).

The use of trend analysis methods for climate data identified long-term changes in air temperature in cities depending on the degree of greening and offered recommendations for improving the efficiency of green areas in combating the heat island effect. The data for Kyrgyzstan was compared with similar indicators from developed countries, which identified effective strategies for managing urban green spaces and adapting them to the region's conditions.

A comprehensive approach, including statistical, comparative and spatial analysis, was used to comprehensively assess the role of green spaces in the urban environment, identify the most effective tree and shrub species in terms of improving air quality and biodiversity, and identify promising areas for the development of urban greening policy in a changing climate.

Results

Analysis of statistical data for Kyrgyzstan showed that black poplar (*Populus nigra*) was the most effective among the considered species in many ecological parameters. It had the highest capacity to capture particulate matter (9.8 g/m^2/year) and the most significant level of carbon dioxide absorption (24 kg/tree/year). In addition, poplar showed high efficiency in the absorption of nitrogen oxides (3.6 g/m^2/year) and sulphur dioxide (2.4 g/m^2/year), which indicated its ability to filter harmful gases from automobile emissions and industrial activities. Data were obtained through analysis of landscaping programmes, field measurements and a comparative study of the effectiveness of tree plantations in urban environments. However, despite these positive qualities, poplar also had some disadvantages. It was characterised by rapid growth, which required regular sanitary pruning and maintenance. In addition, its pollen and fluffy seeds could cause allergic reactions in the population, which limited its use in certain areas of Bishkek (Table 1).

Table 1. Efficiency of tree and shrub plantations in reducing air pollution in Kyrgyzstan (2024)

Plant species	Capture of particulate matter (PM2.5, PM10), g/m²/h	CO_2 absorption, kg/tree/h	NO_x absorption, g/m²/h	SO_2 absorption, g/m²/h	Temperature drop, °C
Black poplar (*Populus nigra*)	9.8	24	3.6	2.4	4.5
Tatar maple (*Acer tataricum*)	7.5	18	2.9	1.8	3.7
Small-leaved linden (*Tilia cordata*)	6.9	16	2.5	1.7	3.2
Hanging birch (*Betula pendula*)	6.2	14	2.3	1.5	2.8
Scots pine (*Pinus sylvestris*)	8.7	22	3.2	2.1	4
Tien Shan spruce (*Picea schrenkiana*)	7.9	21	3	2	3.9
Honeysuckle (*Lonicera*)	4.1	9	1.8	1.2	2
Cotoneaster (*Cotoneaster*)	4.7	11	2	1.3	2.2

Source: compiled by the authors based on M. Orlova (2023)

Tatar maple (*Acer tataricum*) also demonstrated high efficiency in air purification, although its performance was slightly lower than that of poplar. It absorbed 7.5 g/m²/year of particulate matter and 18 kg/tree/year of carbon dioxide, with a temperature reduction effect of 3.7°C. This confirmed that maple could be used as one of the main species for urban landscaping in Kyrgyzstan. Its advantage was its resistance to pollution, high longevity and ability to support biodiversity, which made it particularly valuable for creating urban parks and green spaces.

Small-leaved linden (*Tilia cordata*) showed similar results to maple, demonstrating the ability to capture 6.9 g/m²/year of particulate matter and absorb 16 kg/tree/year of CO_2. Its importance lies in its ability to attract pollinators, which had a positive impact on the biodiversity of urban ecosystems. However, linden required more care and regular irrigation, which could be a limitation in the arid climate of Kyrgyzstan.

Among coniferous trees, the highest efficiencies were recorded for common pine (*Pinus sylvestris*) and Tien Shan spruce (*Picea schrenkiana*). Pine demonstrated the ability to capture 8.7 g/m²/year of particulate matter and absorb 22 kg/tree/year of carbon dioxide and efficiently absorbed nitrogen oxides (3.2 g/m²/year) and sulphur dioxide (2.1 g/m²/year). Tien Shan spruce showed similar results, although its particulate matter uptake was slightly lower (7.9 g/m²/year). An important advantage of conifers was their ability to maintain air purification efficiency during winter when deciduous trees lose their leaves and cease to fulfil their filtering function. This indicated the need to include conifers in urban landscaping programmes, especially in areas with high air pollution.

Shrub plantations demonstrated moderate effectiveness in reducing air pollution but played an important role in maintaining biodiversity and creating barrier zones along roads and industrial areas. Honeysuckle (*Lonicera*) had relatively low particulate matter capture (4.1 g/m²/year) and CO_2 uptake (9 kg/tree/year), but its advantages were drought tolerance and its ability to stabilise the soil by preventing erosion. Cotoneaster (Cotoneaster) performed slightly better, capturing 4.7 g/m²/year of particulate matter and absorbing 11 kg/tree/year of CO_2. Its main advantage was its small size, which made it suitable for landscaping courtyard areas and transport interchanges.

The analysis of temperature impacts showed that trees with a wide crown, such as poplar, maple and linden, had the most pronounced effect on temperature reduction. In areas of Bishkek with their dense planting, temperatures decreased by 3.2-4.5°C, indicating a significant contribution of these plants to reducing the heat island effect (Kulikov *et al.*, 2023). Conifers also contributed to temperature reduction, but their effect was less pronounced, ranging from 3.9-4°C (Air Quality Central Asia Dialogue Platform, 2024). Shrubs had a minimal impact on the temperature regime but provided additional shade and reduced moisture evaporation from the soil surface. The biodiversity indicators confirmed that maple, linden and spruce were of the greatest importance for maintaining the urban ecosystem. These species provided habitat for pollinating insects, birds and small mammals, which helped to maintain the ecological balance in the urban environment. At the same time, poplar and birch showed only an average ability to maintain biodiversity, which was explained by their lower attractiveness for local animal and insect species.

Thus, the data analysis showed that the most effective tree species for urban greening in Kyrgyzstan were poplar, maple, pine and spruce (Bakirov *et al.*, 2021). Poplar provided maximum filtration of particulate and gaseous pollutants but required regular maintenance. Maple and linden combine high CO_2 absorption capacity with biodiversity support, making them optimal for urban parks and squares (Kunakh *et al.*, 2021). Coniferous trees significantly improved the air cleaning in winter and provided a moderate temperature drop. Shrubs had a supporting effect, protecting urban areas from pollution and stabilising soil processes.

The first significant indicator analysed was the average percentage of green space in cities. In Kyrgyzstan, it was only 12%, which was much lower than the level of green space in developed countries (Momosheva *et al.*, 2024). In Singapore, this indicator reached 47%, which was explained by the active implementation of the "garden city" concept, including vertical gardening, park areas and urban forests (Barboza *et al.*, 2021; Feng, 2021). In Germany, Canada and Sweden, the percentage of green space was also high (40%, 38% and 44%, respectively), demonstrating systematic public policies to protect and expand green spaces (Table 2).

Table 2. Comparative analysis of green areas in Kyrgyzstan and other countries (Singapore, Germany, Canada, Sweden)

Country	Kyrgyzstan	Singapore	Germany	Canada	Sweden
Average percentage of green space in cities (%)	12	47	40	38	44
Number of trees per 1000 inhabitants (pcs.)	45	150	110	130	140
Average temperature drop in summer (°C)	3.5	5.2	4.8	4.5	4.7
CO_2 uptake (kg/m^2/year)	18	27	25	24	26
Main types of green spaces	Poplar, maple, pine, ale	Palms, ficuses, rain trees	Beech, oak, linden, maple	Maple, ale, pine, aspen	Pine, ale, birch, linden
The number of parks and green areas in the capital (pcs.)	23	350	295	310	270
Green spaces per capita (m^2)	9	50	38	42	45

Table 2, Continued

Country	Kyrgyzstan	Singapore	Germany	Canada	Sweden
Level of investment in greenery (million USD/year)	5	320	280	260	275
Greening strategies	Local initiatives and government programmes	Vertical gardening, water-saving technologies	Regeneration of natural areas, eco-parks	Comprehensive forest protection programmes	Adaptive landscaping, sustainable forest plantations

Source: compiled by the authors based on Biosphere reserves for man and nature (n.d.), S. Tsoka *et al*. (2021), Canada's climate plans and targets (2023), United Nations Environment Programme (2023), L. Blecken *et al*. (2025), Food and Agriculture Organisation of the United Nations (2025), National Environment Agency (2025)

Another important parameter was the number of trees per 1,000 inhabitants. In Kyrgyzstan, this indicator was 45 trees, which was the lowest among the countries studied. In contrast, Singapore had 150 trees per 1,000 inhabitants, and Germany, Canada and Sweden had 110, 130 and 140 trees, respectively. The high density of trees in these countries provided improved air quality, reduced noise levels and increased the overall environmental sustainability of urban environments (Quaranta *et al*., 2021; Vasylyshyn *et al*., 2023). The average summer temperature reduction also demonstrated significant differences between countries. In Kyrgyzstan, the average temperature reduction due to green spaces was 3.5°C, while in Singapore it reached 5.2°C, and in Germany, Canada and Sweden 4.8°C, 4.5°C and 4.7°C, respectively. This was attributed to the high density and diversity of tree and shrub plantations in developed countries, as well as the use of modern landscaping technologies such as vertical gardening and the use of green roofs (Meo *et al*., 2021).

The CO_2 absorption indicator confirmed the importance of green spaces for the urban ecosystem. In Kyrgyzstan, this indicator was 18 kg/m_2/year, which was the lowest value among the countries studied. In Singapore, trees absorbed 27 kg/m_2/year, and in Germany, Canada and Sweden 25, 24 and 26 kg/m_2/year, respectively. The high values in developed countries were attributed not only to the large green areas but also to the active support of sustainable forest plantations and the use of ecologically adapted tree species with high carbon sequestration capacity (Romanchuck *et al*., 2017; Kolimenakis *et al*., 2021). Data on the number of parks and green spaces in the capital also revealed significant differences. There were only 23 parks in Bishkek, which was significantly lower than in other countries. Singapore had 350 parks, Germany 295, Canada 310 and Sweden 270. The high number of parks in developed countries has been attributed to long-term government programmes aimed at increasing green space, which has helped to improve the urban environment and public health (Pryshchepa, 2019; Nguyen *et al*., 2021; Bidolakh & Kolesnichenko, 2023).

Another important indicator was the amount of green spaces per capita. In Kyrgyzstan, this indicator was 9 m^2, which was 4-5 times lower than in developed countries. In Singapore, this indicator reached 50 m^2, in Germany 38 m^2, in Canada 42 m^2, and in Sweden 45 m^2. These data confirmed that developed countries created favourable conditions for the expansion of green spaces, while in Kyrgyzstan there was a shortage of places for planting trees and shrubs (Khan *et al*., 2022). No less significant factor was the level of investment in landscaping. In Kyrgyzstan, only 5 million USD per year was allocated for landscaping, which is dozens of times less than in developed countries. In Singapore, the figure was USD 320 million, in Germany USD 280 million, in Canada USD 260 million, and in Sweden USD 275 million. High investment in green spaces in developed countries ensured effective restoration of green spaces, support for parks, and the introduction of innovative solutions such as rain gardens and vertical gardens (World Bank, 2023).

The last aspect of the analysis was greening strategies. In Kyrgyzstan, greening was mainly implemented through local initiatives and government programmes, which limited its scale and effectiveness (Green City Action..., 2024). In Singapore, best practices including vertical gardening and water conservation systems were applied, maximising the efficiency of available land resources (Klaus & Kiehl, 2021). Germany has implemented projects to restore natural areas and create eco-parks (Serra-Llobet *et al.*, 2022), Canada integrated forest protection programmes (Ibrahim & Johansson, 2021), and Sweden adaptive landscaping for climate change (Petersson *et al.*, 2022).

Thus, the analysis demonstrated that the level of urban greening in Kyrgyzstan remained significantly lower than in developed countries. The main constraints were insufficient green space, low tree density, weak support for biodiversity and insufficient funding for greening programmes. In contrast, green infrastructure in developed countries has been actively developing due to high investment, the use of modern technologies and a comprehensive approach to protecting and expanding urban green spaces.

The first parameter to be analysed was CO_2 uptake. The data showed that black poplar absorbed the highest amount of carbon dioxide (24 kg/tree/year), making it one of the most effective species in terms of improving air quality. The high level of CO_2 absorption was explained by intensive physiological growth processes, as poplar is characterised by rapid biomass growth. However, its high-water demand and relatively short life cycle could reduce its long-term ecological sustainability (Fig. 1).

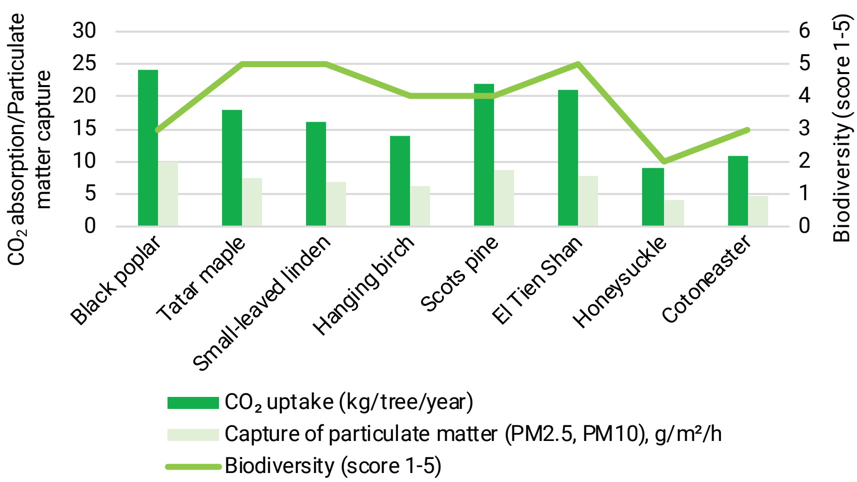

Figure 1. Effectiveness of different types of tree and shrub plants in reducing air pollution and increasing biodiversity

Source: compiled by the authors based on E. Khazieva *et al*. (2022)

Among conifers, common pine and Tien Shan spruce also showed significant carbon dioxide uptake rates of 22 and 21 kg/tree/year, respectively. Their photosynthesis and carbon sequestration capacity were maintained all year round, making them indispensable in urban landscaping, especially in regions with pronounced seasonality. The second important parameter was particulate matter capture (PM2.5, PM10), which also varied according to the morphological characteristics of the plants. The highest efficiency in particulate matter retention was demonstrated by black poplar, which retained 9.8 g/m^2/year. This was explained by its broad crown and high density of leaf cover. However, this indicator required regular maintenance, as the accumulation of pollutants on leaves could reduce their photosynthetic activity.

Common pine and Tien Shan spruce also showed good results in particulate matter retention (8.7 and 7.9 g/m^2/year, respectively). Coniferous trees, having needle-shaped leaves, retained not only dust particles but also gaseous pollutants. Their air filtration capacity remained high in winter when deciduous trees lost their efficiency. Deciduous species such as Tatar maple, small-leaved linden and birch showed moderate results in particulate matter capture (7.5, 6.9 and 6.2 g/m^2/year, respectively). These trees were characterised by medium crown density, but their ability to clean the air was enhanced by their high tolerance to urban conditions and long growing seasons.

The last parameter of the analysis was the impact of the plantations on biodiversity. The assessment was carried out on a 5-point scale, with Tatar maple, small-leaved linden and Tien Shan spruce having the highest scores (5 points). These species provide optimal living conditions for pollinating insects, birds and small mammals, which contributes to the formation of sustainable urban ecosystems. In contrast, honeysuckle and cotoneaster, being shrubby plantations, received a lower score (2 and 3 points respectively). Despite their ability to create hedges and provide additional protection from pollutants, their contribution to biodiversity was limited. However, such shrubs effectively served as buffer zones, especially along transport routes. Thus, the data analysis confirmed that to achieve the maximum environmental effect in cities, it is necessary to apply an integrated approach to landscaping, combining different types of tree and shrub plantations.

The largest contribution to climate adaptation came from temperature reduction (35%), which confirmed the importance of green spaces in combating the heat island effect. In Bishkek, where the level of greenery remained low, temperatures in the city's central areas could be 5-7°C higher in summer than in suburbs with natural vegetation. With a lack of parks and shady streets, this effect was exacerbated by the high concentration of asphalt and concrete, which absorb solar radiation. In contrast, in Singapore, where urban architecture was integrated with vegetation, dense tree canopies and green roofs provided a 3-5°C drop in air temperature. In Berlin and Stockholm, green corridor technologies were also actively used to ensure the circulation of cool air and reduce overheating of built-up areas (Fig. 2).

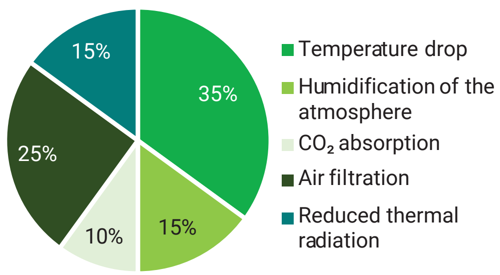

Figure 2. The role of green spaces in urban climate adaptation and heat island mitigation
Source: compiled by the authors based on F. Marando *et al*. (2022)

The second significant climate adaptation mechanism was air filtration (25%), which is particularly relevant for megacities with high levels of pollution. Bishkek suffered from significant emissions of pollutants, including PM2.5 and PM10, due to the operation of industrial enterprises and heavy traffic. The absence of dense green areas along transport routes resulted in high concentrations of harmful substances in the surface layer of the atmosphere. In cities with developed greening programmes, such as Berlin and Ottawa, trees and shrubs were used as natural filters that retain dust and harmful gases. In Singapore, special attention was paid to the introduction of vertical gardens, which provide additional air purification and reduce air temperature in high humidity conditions.

Humidification of the atmosphere (15%) also accounted for a significant share of climate adaptation. In Bishkek, where the arid climate was combined with a small number of water bodies, the lack of greenery led to excessive drying of the air in summer. Trees, with their ability to evaporate moisture through their leaf stomata, contributed to a local increase in humidity and improved the microclimate. In Stockholm and Ottawa, where climatic conditions are more humid, landscaping was used to maintain the natural balance of evaporation and protect against overheating. In Singapore, evaporative cooling was actively used in architecture: vertical greening systems provided additional humidification of the air, which reduced stress on the human body.

Another important adaptation mechanism was the reduction of thermal radiation (15%), which is especially relevant for densely built-up cities. In Bishkek, due to insufficient landscaping, buildings and roads heated up during the day and radiated heat at night, increasing the average daily air temperature. In Berlin, where "green streets" with dense plantings along the roads and shady park areas were practised, the effect of thermal radiation was much lower. In Singapore and Ottawa, the widespread use of green roofs and green facades reduced the heat load on buildings, which reduced the need for air conditioning and lowered overall energy consumption.

CO_2 absorption (10%) was also an important function of green spaces, especially in the context of global climate change. In cities with high industrialisation and heavy traffic, carbon dioxide emissions remained at critical levels. In Bishkek, where environmental programmes to reduce CO_2 emissions were underdeveloped, green spaces could play a more significant role in carbon sequestration. In Ottawa and Stockholm, urban forests served as natural CO_2 "sinks", reducing carbon dioxide concentrations and improving air quality. In Singapore, innovative green facade technologies complement traditional trees, increasing the city's overall carbon sequestration capacity.

The analysis showed that green spaces are central to the climate adaptation of cities, reducing the heat island effect, improving air quality and providing comfortable living conditions. In Bishkek, where the density of green areas remained low, high temperatures in the urban environment, increased air pollution and low humidity levels were observed, which negatively affected the microclimate. In contrast, in Singapore, Berlin, Ottawa and Stockholm, greenery has been integrated into urban architecture, providing multi-level climate adaptation.

Discussion

The results of the study confirmed the significant impact of tree and shrub plantations on improving the environmental situation in Kyrgyz cities. The study determined that green spaces effectively reduce air pollution by retaining particulate matter (PM2.5 and PM10) and absorbing CO_2. The most effective species were black poplar, Tatar maple, lodgepole pine and Tian Shan spruce, which have a high air filtration capacity. At the same time, shrubs such as honeysuckle and cotoneaster showed moderate efficiency but played an important role in creating buffer zones along roads. A comparative analysis of the greening of Kyrgyzstan and successful countries (Singapore, Germany, Canada, Sweden) revealed a significant gap in terms of the area of green spaces and the number of trees per capita. In Singapore, Germany, Canada and Sweden, vertical gardens, green roofs and the integration of green spaces with urban infrastructure are widely used to reduce the heat island effect and improve the microclimate (Kovach *et al*., 2024; Ryzhova *et al*., 2024).

As shown by J.D. Karimi *et al.* (2021b), the ecosystem services of urban landscapes can be significantly improved with proper spatial planning. The study determined that an even distribution of green spaces helps reduce air pollution and improves the climate resilience of urban environments. These results partially coincide with the findings of this study, as the high density of tree and shrub plantations was also found to significantly reduce air pollution and regulate microclimate. However, in contrast to the study by J.D. Karimi *et al.*, the presented study addressed specific plant species, analysing their effectiveness in reducing pollutants and maintaining biodiversity. This makes this study more detailed and applied, as it identifies the most effective tree and shrub species adapted to the climatic conditions of Kyrgyzstan and proposes specific measures for greening. As determined by S. Xie *et al.* (2022), water bodies in combination with green spaces are key to urban biodiversity conservation, especially among bird populations. The authors' study in Beijing showed that areas adjacent to water bodies have higher avifauna abundance due to the combination of water and vegetation. This study also confirmed that the density and diversity of tree plantations have a positive effect on biodiversity, but the main focus is on their ability to reduce air pollution and increase the climate resilience of cities. This study does not look at the impact of water bodies but focuses on terrestrial ecosystems. This makes it more relevant to regions with limited water bodies, such as Kyrgyzstan, where special attention needs to be paid to urban greening to improve the environmental situation.

As determined by D.J. Kotze *et al.* (2022) established that urban forests provide favourable conditions for invertebrates, including insect pollinators, which play a key role in maintaining ecosystem functions. The study demonstrated that the higher the density and species diversity of tree plantations, the greater the number of insects that can be observed in urban environments. The data overlap with the results of this study, as the role of green spaces in maintaining biodiversity was also identified. However, in contrast to the study by D.J. Kotze *et al.*, this study addressed the effects of tree plantations on air quality and climate adaptation rather than fauna. In addition, a quantitative analysis of the effectiveness of individual plant species was conducted, which makes this study more applicable and useful for the development of urban greening programmes in Kyrgyzstan. As demonstrated by A. Francini *et al.* (2022), ornamental plants can significantly contribute to the provision of ecosystem services, including air filtration and temperature regulation. Their study confirmed that the use of ornamental plants can play an important role in creating sustainable urban ecosystems. The data overlaps with the presented study, as it is also confirmed that green spaces have a positive impact on urban microclimate and air quality. However, this study focuses predominantly on tree and shrub species, making it more relevant for the development of long-term greening strategies. In addition, a detailed quantitative assessment of their ecological effectiveness was conducted, which provides more specific recommendations for selecting plants for urban landscaping in Kyrgyzstan.

As noted by C. Farrell *et al.* (2022), it is necessary to account for the ecological resilience of the plant species used to improve the efficiency of green infrastructure. The study demonstrated that the introduction of native and adapted tree species contributes to more stable and resilient urban ecosystems. This study supports this conclusion as it is also discovered that the selection of certain tree and shrub species has a significant impact on reducing air pollution and regulating temperature in urban environments. However, the presented study quantitatively analyses the effectiveness of specific plant species, which makes it more detailed. These results are particularly important for Kyrgyzstan, where it is necessary to address local climatic conditions and select the most appropriate tree and shrub species for urban landscaping. As revealed by K. Pukowiec-Kurda (2022), the urban ecosystem services assessment index accounts for pollution levels, climate resilience and biodiversity in urban greening planning. The study determined that cities with high levels of greening show better indicators of ecological conditions and comfort of the urban environment. These results partially coincide with this study as the relationship between green spaces and environmental parameters of the urban environment was also found. However, in contrast to the index approach of K. Pukowiec-Kurda, this study analysed specific plant species in detail, which allows for the development of targeted greening strategies adapted to the climatic conditions of Kyrgyzstan. This renders the results more applied and useful for the development of specific recommendations to improve environmental policy in the cities of the region.

K.S. Prendergast *et al.* (2022) determined that the composition of native bee populations in urbanised landscapes depends on a variety of factors including vegetation density, availability of flowering plants and landscape diversity. The study determined that cities with a high degree of landscaping have a greater species diversity of bees, which contributes to biodiversity. The data overlaps with the results of this study, which also identified the role of tree and shrub plantations in maintaining ecosystem functions. However, this study emphasises the impact of green spaces on air quality and microclimate regulation. Thus, the presented results add to existing knowledge by expanding the understanding of how urban vegetation contributes not only to biodiversity but also to pollution and temperature reduction.

As shown by H. Sensoy & M. Tanyel (2022), evergreen trees and conifers are substantial in regulating the water balance of the urban environment, especially in conditions of heavy rainfall. Their study confirmed that such plantations reduce the rate of precipitation, reducing soil erosion and increasing the ability of soils to absorb moisture. The data partially coincide with the results of this study, as it also confirmed that tree and shrub plants perform significant ecological functions in the urban environment. However, this study does not focus on water balance, but rather on the impact of vegetation on climate adaptation and air purification. Nevertheless, these results can be incorporated into the selection of tree species for urban greening in Kyrgyzstan, ensuring not only improved microclimate but also optimal water management.

As demonstrated by M.C. Jung *et al.* (2021) the heterogeneity of the urban landscape significantly influences the relationship between tree cover density and surface temperature. The study determined that dense green spaces contribute to a significant decrease in temperature, especially in areas with high built-up areas. These results are in full agreement with the findings of this study, which also found that tree and shrub plantations play a key role in reducing the heat island effect. However, in contrast to the study by M.C. Jung *et al.*, this study places greater emphasis on tree and shrub plant species and their effectiveness in reducing temperature. This approach allows not only to confirm the overall effect of landscaping, but also to identify specific plant species most suitable for the climatic conditions of Kyrgyzstan.

As identified by A. Aziz *et al.* (2023), rapid changes in peri-urban landscapes impact the provision of ecosystem services including temperature regulation, air quality and social amenities. Their study established that intensive urban development leads to the reduction of green spaces, which negatively affects the ecology and comfort of residents. These results partially correlate with the current study as a significant role of green spaces in improving the quality of life in urban areas was also identified. In contrast to A. Aziz *et al.*, this study concentrated on specific tree and shrub species and their effectiveness in reducing air pollution and regulating microclimate. This makes the results more practical for developing targeted landscaping strategies adapted to the conditions of Kyrgyzstan. Thus, the presented results confirm the main conclusions of previous studies but also expand them by offering a detailed quantitative assessment of the impact of tree and shrub plantations on reducing air pollution, regulating temperature and maintaining ecosystem functions in cities.

Conclusions

The study revealed significant differences in the ecological functions of different plant species. The most ecologically efficient were black poplar (*Populus nigra*) absorbing 24 kg CO_2 annually and trapping 9.8 g/m^2 of particulate matter per year, Tatar maple (*Acer tataricum*) with 18 kg CO_2 and 7.5 g/m^2, respectively, and small-leaved linden (*Tilia cordata*) 16 kg CO_2 and 6.9 g/m^2 of particulate matter. The same species contributed to the most significant cooling of the environment during the hot season by 3.5-4.5°C. A comparative analysis of green spaces has shown that Kyrgyzstan lags significantly behind the world leaders. The share of green spaces in the country's cities is only 12%, which is significantly lower than in Singapore (47%), Germany (40%), Canada (38%) and Sweden (44%). There are only 45 trees per 1,000 inhabitants in Kyrgyzstan, compared to 150 in Singapore, 110 in Germany, 130 in Canada and 140 in Sweden. The Kyrgyz capital has 9 m^2 of green space per inhabitant, compared to 50 m^2 in Singapore, 38 m^2 in Germany, 42 m^2 in Canada and 45 m^2 in Sweden.

Leading countries are actively implementing progressive greening practices: Singapore is developing vertical greening and water-saving technologies, Germany is restoring natural areas and creating eco-parks, Canada is implementing programmes to protect forests, and Sweden is applying adaptive greening methods. To improve the environmental situation, cities in Kyrgyzstan need to expand the area of green spaces and increase funding for environmental programmes. Currently, investments in green spaces amount to only USD 5 million per year, which is not comparable to Singapore (USD 320 million) and Germany (USD 280 million). It is recommended to develop integrated strategies that include greening rooftops, expanding park areas and preserving existing plantings. The limitations of this study include insufficient consideration of the seasonal dynamics of plant efficiency and the specifics of climatic conditions in different regions of the country. Promising areas for further research include studying long-term trends in greening, assessing the role of water bodies and developing adaptation strategies for the urban landscape to climate change.

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None.

Conflict of Interest

None.

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Екологічна роль деревних і чагарникових насаджень у міських ландшафтах

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Анотація. Метою дослідження було визначення впливу зелених насаджень на екологічну стійкість міст та визначення найбільш результативних методів озеленення. У рамках дослідження проведено аналіз впливу різних видів деревних і чагарникових рослин на зниження рівня забруднювальних речовин, включно з твердими частинками (PM2.5 і PM10) і вуглекислим газом, а також їхньої здатності до регулювання температурного режиму та створення комфортних кліматичних умов. Результати засвідчили, що найефективнішими видами рослин для міського озеленення були тополя чорна, що має найбільшу здатність до фільтрації твердих частинок (9,8 г/м^2/рік PM2.5 і PM10) і високий рівень поглинання CO_2 (24 кг/дерево/рік), клен татарський, що забезпечує значне зменшення забруднення повітря (7,5 г/м^2/рік PM2. 5 і PM10) і вловлювання CO_2 (18 кг/дерево/рік), сосна звичайна, яка показувала високу ефективність у зниженні рівня твердих частинок (8,7 г/м^2/рік PM2.5 і PM10) і в поглинанні вуглекислого газу (22 кг/дерево/рік), а також смерека тянь-шаньська, що поєднувала здатність до очищення повітря (7,9 г/м^2/рік PM2.5 і PM10) з високим рівнем поглинання CO_2 (21 кг/дерево/рік). Ці види рослин демонструють високу здатність до поглинання забруднювальних речовин і зниження температури повітря в літній період на

3,2-4,5 °C. У Киргизстані площа зелених насаджень у містах становить 12 % від загальної території, що значно нижче, ніж у розвинених країнах, таких як Сінгапур (47 %), Німеччина (40 %), Канада (38 %) і Швеція (44 %). У столиці Киргизстану, Бішкеку, на одного жителя припадає 9 $м^2$ зелених насаджень, тоді як у Сінгапурі цей показник сягає 50 $м^2$, а в Німеччині 38 $м^2$. Аналіз міжнародного досвіду виявив, що розвинені країни активно застосовували інноваційні методи озеленення. У Сінгапурі широко використовували вертикальні сади й технології водозбереження, у Німеччині пріоритет надавали регенерації природних територій і створенню екопарків, у Канаді реалізовували комплексні програми захисту лісів, а у Швеції впроваджували адаптивні методи озеленення та стійкі лісопосадки. Ці заходи сприяли значному поліпшенню екологічної стійкості міського середовища. Висновки дослідження підкреслюють необхідність комплексного підходу до озеленення міст Киргизстану з урахуванням вибору найстійкіших деревних і чагарникових видів, а також впровадження сучасних технологій озеленення

Ключові слова: сталий розвиток; зелена інфраструктура; кліматична адаптація; біорізноманіття; урбаністичне озеленення

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Forestry and rural development in Albania: Integrating forestry and agricultural practices for a sustainable future in the economy

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Abstract. The integration of forestry and agricultural practices contributes to the environmental sustainability and economic development of rural areas, especially in regions with soil degradation. The purpose of the study was to assess the impact of agroforestry systems on land productivity, conservation of natural resources, and socio-economic development of local communities; to identify barriers and prospects for their further implementation. The methodology included statistical analysis, comparison of the effectiveness of various agroforestry models, and assessment of economic and environmental indicators. The study showed that the area of land involved in agroforestry is 150-200 thousand hectares (10% of agricultural land). Forest and pastoral systems have reduced farmers' feed costs by 20-25%, and the use of mixed agroforestry models has increased crop yields by 14% compared to traditional farming. It was established that the level of organic matter in the soils of such systems is almost twice as high as

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in traditional agricultural landscapes, and erosion processes are reduced by 20-30%. Forest stands within the framework of agroforestry contribute to the conservation of biodiversity, in particular, an increase in the number of useful pollinating insects by 40%, and the restoration of populations of small mammals and birds. It was also found that the decentralisation of forest management has led to the creation of more than 60 forest cooperatives that ensure effective management of forest resources and increase the economic sustainability of local communities. It was found that the main obstacles to the development of agroforestry in Albania are the lack of state support, financial constraints, technological gaps, and low awareness of farmers. The results of the study indicate the need to create financial incentives, develop forest cooperatives, spread innovative technologies, and expand information support for farmers. The practical significance of the study lies in the development of a comprehensive strategy for sustainable agricultural development, which will contribute to improving land productivity, economic stability of local communities, and adaptation to climate change

Keywords: sustainable development; soil erosion; agroforestry; environmental sustainability; land productivity; economic adaptation

Introduction

Integrating forestry and agricultural practices is a key area for sustainable rural development, especially in countries with high levels of soil erosion and environmental challenges, such as Albania. Land degradation caused by intensive farming and overgrazing negatively affects the productivity of the agricultural sector, which requires the introduction of new approaches to natural resource management. Agroforestry is seen as an effective strategy for preserving soil fertility, regulating water balance, and improving the economic stability of rural communities. However, studies indicate a lack of development of mechanisms for financial support of agroforestry and a lack of clear regulatory measures, which limits its implementation at the national level. In addition to environmental aspects, the relevance of the study is also conditioned by the economic feasibility of developing agroforestry, which allows farmers to diversify their sources of income through the cultivation of tree crops, medicinal plants and the development of ecotourism. In the EU countries, such practices receive significant financial support, while in Albania, incentive mechanisms remain insufficiently developed.

The analysis of scientific sources showed a growing interest in integrating forestry and agricultural practices as a means of ensuring sustainable development and economic growth in Albania. Studies have confirmed the importance of combining economic, environmental and policy approaches to regulating agroforestry, but have identified a number of gaps in understanding the long-term consequences of these processes. The study by E. Kumi (2024) focused on assessing environmentally sustainable economic development in Albania. The researcher proved that an unbalanced policy in the field of environmental management restrained the potential for sustainable growth and required more effective mechanisms of state support for agroforestry. M. Bojović *et al*. (2024) analysed the possibilities of agroforestry systems for providing sustainable energy in the Western Balkans. The researchers found that agroforestry can help to diversify energy resources and reduce greenhouse gas emissions.

The policy of agricultural development in the context of European integration of Albania and North Macedonia was studied by A.M. Stojcheska *et al*. (2024). The researchers have found that the harmonisation of agricultural policy with EU requirements required a broader introduction of environmentally sustainable land use methods, in particular, agroforestry. The study by E. Gjokutaj (2021) considered the impact of economic and fiscal policies on agriculture in Albania. The researcher proved that financial constraints and regulatory barriers negatively affected the introduction of agroforestry, but its development could contribute to improving the efficiency of agricultural production.

The study by I. Canfora (2025) reviewed the implementation of pre-accession assistance tools for rural development. The researcher found that financial support for agroforestry could become an important area of the national policy for improving the economic stability of the agricultural sector. The study by J. Veleshnja (2024) showed that the development of ecotourism contributed to the improvement of the economic situation in rural areas. The researcher proved that the combination of forestry and agricultural resources created additional opportunities for diversification of income sources.

The challenges of sustainable rural development were addressed in the paper by E. Lika (2021). The researcher found that the integration of forestry and agricultural practices helped to reduce the risks of land degradation and increase the productivity of the agricultural sector. Ultimately, B. Kullolli (2023) analysed the legal regulation of the use of forest resources. The researcher found that the lack of a clear legislative framework limited the development of agroforestry, which required the development of new regulatory initiatives. Overall, an analysis of available research has confirmed the importance of integrating forestry and agricultural systems for Albania's economic and environmental sustainability. The scientific literature revealed a lack of comprehensive research on the long-term economic and environmental effects of agroforestry, which justified the need for further research in this area.

The purpose of this study was to assess the current state of agroforestry in Albania, identify the main challenges of its implementation, and develop recommendations for adapting successful European practices to local conditions. To achieve this goal, several tasks were set: to assess the current state of agroforestry in Albania and the main environmental challenges associated with land degradation; to carry out an economic analysis of the effectiveness of various models of agroforestry and their impact on the profitability of farms; to develop recommendations for improving the state policy of support for agroforestry, in particular, financial incentives and regulatory mechanisms aimed at improving the efficiency of integrated land use systems.

Materials and Methods

The main sources of information were data from the Ministry of Agriculture and Rural Development of Albania, which contain detailed information on the area of forestry and agricultural land, the level of soil erosion, the productivity of agroforestry systems and the level of income of farms. An important component of the study was materials from the Food and Agriculture Organisation (2025), which highlight the impact of agroforestry on yields, economic stability of rural communities, and opportunities for adaptation to climate change. The analytical reports of the European Forestry Institute (Bojović *et al*., 2024), which contain data on the economic efficiency of various agroforestry models and their contribution to the development of regional agricultural ecosystems, were also used.

The method of economic analysis was used to assess the effectiveness of agroforestry systems in comparison with traditional agriculture. Land productivity, farmers' expenses for feed and fertilisers, and additional sources of income from agroforestry (for example, growing wood, fruit crops, medicinal plants, honey) were investigated. The analysis of financial barriers included the study of the lack of subsidies, limited credit opportunities, and low level of state support for farmers implementing agroforestry systems.

The forecasting method was used to determine possible scenarios for the development of agroforestry in the short and medium term. Econometric modelling was performed, which included an analysis of changes in yields, farmers' income levels, and the expansion of land areas used for agroforestry. The model variables included indicators of soil erosion, precipitation, average annual temperature, and economic costs of farming (Ministry of Environment of Albania, 2023). This allowed assessing the effectiveness of possible policy measures and financial incentives to support farmers.

A comparative analysis of the main models of agroforestry used in Albania, in particular forest-pastoral systems, forestry and protective forest belts, was carried out. The economic efficiency, land productivity, and environmental impact of each model were evaluated. The analysis was based on quantitative indicators, including yield levels, farmers' incomes, and reduced feed costs. The study analysed the international experience of the EU countries, in particular Germany and France, in implementing agroforestry practices.

The influence of agroforestry systems on soil condition and water balance was assessed. The level of organic matter in soils, changes in humus content and indicators of water retention capacity in regions where agroforestry systems were introduced were investigated. The analysis of erosion processes was carried out, which helped to determine the effectiveness of protective forest belts and forest-pastoral systems in reducing land degradation.

Results

The integration of forestry and agricultural practices in Albania is an important aspect of sustainable rural development, contributing to the conservation of natural resources, increasing land productivity and strengthening the economic potential of local communities. The total area of forest land in the country is approximately 1.05 million hectares, which is about 36% of the total territory of the country. The area of agricultural land reaches 695 thousand hectares, of which a significant part was subjected to erosion processes due to intensive agriculture and overgrazing of livestock. In the context of land degradation, an important area has become the introduction of agroforestry systems that help to stabilise soils, regulate water balance, and increase the stability of agricultural landscapes.

The area of land used for agroforestry is approximately 150-200 thousand hectares, which corresponds to 10% of the total area of agricultural land (Food and Agriculture Organization, 2025). The main regions where such practices are actively developing are mountainous areas in the north and centre of the country, in particular, the districts of Kukes, Diber, and Korcha. The introduction of tree stands within agricultural land has become widespread among local farmers, which is explained by the positive impact of such systems on maintaining soil fertility and protecting crops from climatic extremes. Of particular importance is the forest-pastoral system, which combines tree cultivation with grazing, which is a traditional practice in many Albanian regions.

A comparative analysis of various models of agroforestry shows that land productivity significantly depends on the type of integrated system. In particular, forestry demonstrates the highest yield among agroforestry models, since the combination of fruit trees with field crops helps to preserve soil moisture and improve soil structure. For comparison, farmers using forest pastoral systems report a 20-25% reduction in feed costs, since livestock has access to natural feed sources in forest ecosystems (Bojović *et al.*, 2024). Protective forest belts show the best results in reducing erosion, which is important for regions with intensive agricultural production.

Among the typical models of integration of forestry and agriculture, forest-pastoral systems, forest gardening, and the creation of protective forest belts are distinguished. Forest-pastoral systems are the most common form of use of forest areas in agriculture, especially in foothill areas, where oak and chestnut forests serve as a natural food base for sheep and goats. Forestry, in particular, the cultivation of nut and fruit trees (for example, almonds, figs, pomegranates) in combination with traditional field crops, shows stable growth, since this model provides additional sources of income for farmers. Protective forest belts are mainly used in areas with intensive agricultural production, their purpose is to reduce wind erosion and preserve soil moisture (Table 1).

Table 1. Main models of integration of forestry and agricultural practices in Albania

Model type	Main features	Distribution regions	Economic advantages	Environmental impact on forest ecosystems
Forest and pastoral system	Grazing of livestock in forest areas	Kukes, Diber, Lezha	Increase livestock productivity, reduce feed costs	Preserving forest cover, maintaining biodiversity, and reducing fire risks through vegetation control
Forestry	Combining fruit trees with traditional crops	Korcha, Berat, Vlora	Income diversification, increasing soil fertility	Improving the soil structure, increasing the number of useful pollinating insects, and reducing erosion
Protective forest belts	Forest belts around agricultural land	Durres, Fier, Tirana	Reducing erosion, improving the water regime	Microclimate stabilisation, wind erosion reduction, drought protection, and support for local ecosystems
Forest cooperatives	Collective forest management by local communities	Northern and central regions	Improving management efficiency, improving community well-being	Restoration of forest ecosystems, reduction of illegal logging, conservation of biodiversity through rational use of resources

Source: compared by the authors based on European Commission (2023), Ministry of Environment of Albania (2023), M. Bojović *et al*. (2024), Food and Agriculture Organization (2025)

The policy of decentralising forest management, which began in 2015, has played a key role in the development of Integrated forestry and agricultural systems. According to the new management model, a significant part of the forest areas was transferred to the disposal of local authorities, which allowed communities to independently develop sustainable forest management strategies (Ministry of Environment of Albania, 2023). One of the positive results of this process was the creation of more than 60 forest cooperatives that ensure effective management of natural resources and contribute to the economic development of local communities. However, decentralisation has also revealed a number of problems, including a lack of funding for local administrations and difficulties in controlling illegal logging.

In addition to financial and regulatory barriers, social factors also play an important role in the development of agroforestry. A survey of farmers in the regions of Kukes, Diber and Korcha showed that only 35% of respondents are familiar with the benefits of agroforestry, and another 40% believe that the introduction of tree stands can reduce their productivity in the short term (Food and Agriculture Organization, 2025). One of the main reasons for the low level of implementation is limited access to information, and insufficient consulting support from government agencies and research centres. In EU countries such as Germany and France, the introduction of agroforestry practices was conditioned by active information campaigns and state training programmes for farmers. In Germany, the Agroforestry-Förderung programme has been in operation since 2005, which provides farmers with subsidies of up to 200 EUR/ha annually for the integration of tree stands into agricultural land, which has increased the area of agroforestry by 15% over the past decade. In France, under the Plan de Développement Rural, farmers receive compensation for the creation of protective forest belts and mixed systems, which has led to an increase in agroforestry areas by 25% since 2010. Both countries actively use information campaigns and educational programmes: in Germany, the Deutscher Agroforstverein initiative organises seminars and online platforms for farmers, while in France, the National Institute INRAE has developed educational modules for agricultural colleges, through which more than 5,000 farmers have received specialised training. Scientific and technical support, including the use of drones to monitor the condition of trees and soils, has reduced maintenance costs by 30%. Environmental results are also impressive: in Germany, forest-pastoral systems have reduced CO_2 emissions by 2.5 tonnes/ha/year, and in France, protective forest belts increased the yield of vineyards by 12-18% (European Commission, 2023).

One of the main limitations of the introduction of agroforestry systems remains the low level of funding for farmers who want to apply these methods. Currently, Albania does not have special subsidies or tax incentives for farmers implementing agroforestry, which significantly limits the development opportunities of the sector. Most international funding programmes, such as the Global Environment Facility and the United Nations Development Programme (2024), are aimed at universal forest conservation rather than promoting the integration of forestry and agricultural practices. Compared to EU countries such as France or Germany, where farmers receive up to 200 EUR/ha of annual support for agroforestry, Albania has not yet created an effective financial mechanism to encourage this area.

These data indicate a significant potential for integrating forestry and agricultural practices in Albania. Through this interaction, the conservation of natural resources is achieved, land productivity increases, and the economic opportunities of the rural population are improved. However, the further development of such models requires comprehensive government support, including funding for local initiatives, infrastructure development, and dissemination of scientific knowledge to farmers.

Integration of forestry and agricultural practices is a key approach to ensuring the environmental sustainability of agricultural landscapes. In Albania, these systems contribute to improving soil fertility, preserving biodiversity, and stabilising the water balance. Given the high level of erosion processes in the mountainous and foothill regions of the country, the introduction of agroforestry systems plays an important role in reducing the risks of degradation of natural resources and increasing land productivity.

Agroforestry contributes to the restoration of soil fertility, which is especially important in regions with high erosion rates. Planting perennial trees in combination with agricultural crops reduces wind and water erosion, which is confirmed by research by the Ministry of Agriculture and Rural Development of Albania. Increasing the level of organic matter in soils due to leaf litter and root exudates of trees contributes to the formation of a stable humus structure, which improves the water retention capacity and microbiological activity of soils. In regions where mixed forest pastoral systems are used, the level of erosion has decreased by 25-30% compared to traditional pastures. Table 2 shows the impact of agroforestry on soil indicators.

Table 2. Impact of agroforestry on soil and ecosystem indicators

Indicator	Traditional agriculture	Agroforestry	Forest ecosystems without agricultural influence
Organic matter level (%)	1.5	3	4.5
Humus content (%)	2.5	4	5.2
Erosion reduction (%)	0	20	50
Soil moisture retention capacity (%)	35	50	65
Forest floor density (t/ha)	0.5	1.8	3
Microbial content in the soil (species/gramme of soil)	10^4	10^5	10^6
Soil carbon reserve (t/ha)	3.2	6.8	9.5
Biodiversity of litter insects (species/m^2)	4-6	12-15	20-25
Number of useful fungi in the soil (U/g)	50	130	250
Ecosystem stability (rating)	Low	Average	High

Source: compared by the authors based on M. Bojović *et al*. (2024), Food and Agriculture Organization (2025)

The data in Table 2 show that the level of organic matter in soils where agroforestry is used is almost twice as high as in traditional agricultural systems. A similar trend is observed in the humus content, which is directly related to the stability of the soil structure and its fertility. One of the most important indicators is the reduction in the level of erosion, which in integrated systems reaches 20%, while in traditional agriculture this indicator is practically absent due to excessive land exploitation. Analysis of the obtained data from the point of view of ecology and forest resource management indicates significant advantages of agroforestry systems in supporting the ecosystem functions of the soil. In particular, the indicators of moisture retention capacity in such systems are significantly higher than in traditional agriculture, which helps to reduce the risk of soil degradation and improve their resistance to climate change. Although forest ecosystems without agricultural influence have the highest moisture retention capacity, agroforestry can act as an effective intermediate option for optimising the use of natural resources.

The density of forest floor, which is an important indicator of the productivity of forest ecosystems, in agroforestry systems reaches 1.8 t/ha, which is three times higher than in traditional agriculture. This contributes to improved soil microflora, increased biodiversity, and a more efficient carbon cycle, which are important factors in the sustainability of forest landscapes. The content of microorganisms in the soil also shows positive dynamics: their concentration in agroforestry systems is an order of magnitude higher than in traditional agriculture, which indicates active biochemical processes and improvement of the soil ecosystem. An important aspect of the analysis is the carbon Reserve in the soil, which in agroforestry systems is 6.8 t/ha, which is more than twice as high as in traditional agriculture. This indicates that such systems can play an important role in the global carbon balance and be an effective measure to mitigate climate change. The biodiversity of litter insects, which are key indicators of ecosystem stability, also shows a significant improvement: in agroforestry systems, it reaches 12-15 species/m^2, while in traditional agriculture this indicator is minimal.

Special attention should be paid to the number of useful fungi in the soil, which in agroforestry systems reaches 130 U/g, which helps to increase the trophic chain and strengthen the natural mechanisms of nutrient regulation. An important final indicator is the stability of the ecosystem: if traditional agriculture is characterised by low sustainability, and natural forest ecosystems – high, then agroforestry provides an average level of ecological stability, creating a balance between the economic use of land and their ecological potential. In general, these results indicate that agroforestry contributes to improving the ecological state of soils, increasing their productivity and resistance to degradation. In the context of bioeconomics, such systems can play a key role in ensuring the environmentally balanced use of forest resources, contribute to the conservation of biodiversity and be an effective tool for adapting to climate change.

Another important environmental impact is the conservation of biodiversity, especially in the mountainous regions of Albania, where natural ecosystems have undergone significant anthropogenic impacts. The introduction of agroforestry methods contributes to the maintenance of stable ecosystem links between species, which is confirmed by field studies in the Vjosa Region (Bojović *et al.*, 2024). In areas where forestry and mixed crop cultivation systems were introduced, an increase in the number of beneficial pollinating insects was recorded by 40%, and an increase in the diversity of soil microorganisms, which play a key role in maintaining natural processes of organic matter decomposition. In addition, forest stands provide conditions for restoring populations of small mammals and birds, which is an indicator of ecosystem sustainability. The integration of forestry and agricultural practices also contributes to the improvement of the hydrological regime, which is particularly important for maintaining land productivity in the face of climate change. In particular, mixed agroforestry systems contribute to the regulation of surface runoff and the preservation of soil moisture, which reduces the risk of land degradation. The introduction of perennial tree stands in agricultural landscapes helps to stabilise the groundwater level and reduce moisture loss from the soil, which is especially important for arid regions. However, the impact of climate change remains a key challenge for the effective implementation of agroforestry. It is predicted that by 2050, the average annual temperature in Albania will increase by 1.3-2.2°C, which will lead to an increase in evaporation of soil moisture, especially in low-lying areas. In addition, uneven precipitation distribution can lead to more frequent periods of drought, which will negatively affect yields. For example, in the central and southern regions, there is already a decrease in precipitation by 2.1-4.3%, which threatens to reduce the efficiency of traditional agriculture. The introduction of mixed forest-agrarian systems can become a key tool for reducing climate risks, since tree stands help regulate the microclimate, reduce soil erosion, and maintain water balance.

In areas with implemented forest-agrarian systems, the level of soil moisture retention is on average 15-20% higher than in regions with traditional agriculture. Thus, the integration of forestry and agricultural practices has significant environmental benefits, in particular, the preservation of soil fertility, the maintenance of biodiversity, and the improvement of water balance. The implementation of these methods contributes to long-term environmental stability and ensures the adaptation of agricultural landscapes to climate challenges, which is strategically important for the sustainable development of rural areas in Albania. The integration of forestry and agricultural practices not only contributes to the environmental sustainability of agricultural landscapes, but also provides economic benefits for rural communities. The use of agroforestry methods can increase the profitability of farms by diversifying sources of income, increasing land productivity and developing new economic sectors, in particular, ecotourism.

One of the main advantages is to increase profitability by expanding the range of marketable products. Agricultural producers who introduce agroforestry receive income not only from traditional crops, but also from wood, food products (nuts, fruit trees), medicinal plants, honey and mushrooms. Tree stands are the basis of sustainable forest-agrarian systems, as they provide synergy between agricultural production and forest resources. For example, in the Korcha Region, the average profit of farmers before the introduction of agroforestry was 5,000 USD/ha per year, and after the introduction – 6,000 USD/ha per year, which indicates a 20% increase (Food and Agriculture Organization, 2025). This growth is conditioned not only by the diversification of products, but also to the environmental sustainability that trees provide: they reduce soil erosion, improve its structure and create a microclimate favourable for crops.

Another important economic aspect is the assessment of land productivity in agroforestry systems in comparison with traditional agriculture. Studies show that land where an integrated approach is applied (trees+crops) has a yield of 0.5 t/ha higher. In particular, in traditional agriculture, the average yield was 3.5 t/ha, while in agroforestry systems this indicator increased to 4.0 t/ha, which is equivalent to an increase of 14%. A key role in this is played by tree stands, which stabilise the water balance, maintain soil moisture and reduce the impact of climatic extremes, ensuring long-term productivity of land. This is conditioned by improved microclimatic conditions, increased soil moisture levels, and reduced risks of land degradation. Table 3 presents a comparison of the economic indicators of conventional agriculture and agroforestry systems.

Table 3. Comparison of the profitability of agroforestry and traditional forestry

Indicator	Traditional forestry	Traditional agriculture	Agroforestry
Profit per 1 ha (USD/year)	2,000	5,000	6,000
Payback period (years)	20-30	1-3	5-7
Additional sources of income	Wood	None	Wood, nuts, medicinal plants, honey
Investment level (USD/ha)	1,500	500	2,000
Impact on the ecosystem	Moderate, possible negative consequences due to logging	High, soil erosion	Positive, reducing erosion

Source: compared by the authors based on M. Bojović *et al*. (2024), Food and Agriculture Organization (2025)

Analysis of the economic indicators of traditional forestry, traditional agriculture, and agroforestry shows that integrated agroforestry systems have significant advantages in both financial and environmental aspects. One of the key indicators is profitability: revenues per hectare in traditional forestry are about USD 2,000 per year, in traditional agriculture – USD 5,000 per year, while in agroforestry systems this figure reaches USD 6,000 per year. This growth is driven by product diversification, as farmers receive additional income from wood, nuts, medicinal plants, and honey in addition to their main agricultural activities. An important economic factor is the return-on-investment period. Traditional forestry has the longest payback period – from 20 to 30 years, which is conditioned by the slow growth of wood pulp and the need for long-term investments before making the first profit. In traditional agriculture, this period is much shorter and amounts to 1-3 years, which is explained by the annual harvest. Agroforestry shows an intermediate option – 5-7 years, which, although longer than traditional agriculture, is offset by higher profitability and stable incomes in the long term.

Investment costs per hectare in traditional forestry reach USD 1,500 per hectare, which includes reforestation costs, plantation maintenance, and long-term management. In traditional agriculture, the level of investment is lower – about USD 500 per hectare, which is explained by the intensive use of soils without the need for long-term investments in tree crops. At the same time, in agroforestry systems, this figure is USD 2,000 per hectare, since it requires additional investment in forest stands, but at the same time provides a more stable economic effect. From an ecological standpoint, traditional forestry has a moderate impact on ecosystems, but there may be negative consequences due to intensive logging, which can disrupt the balance of forest biocoenoses. Traditional agriculture has the greatest negative impact on the environment, causing soil erosion, reduced humus levels, and loss of biodiversity due to intense agricultural impacts. In turn, agroforestry provides a positive impact on the ecosystem, since the combination of tree stands with agricultural crops helps to reduce erosion processes, improve soil structure and increase biodiversity.

Thus, the results of the analysis show that agroforestry is an effective model of land management that combines economic benefits and environmental sustainability. Such a system can optimise land use, reduce the risks associated with soil degradation, and ensure long-term economic efficiency for farms. In addition, agroforestry can play an important role in the development of a sustainable bioeconomy, as it contributes to maintaining the productivity of agricultural landscapes, preserving ecosystem services, and mitigating the effects of climate change. Another promising area is the development of ecotourism, which is an important source of income for rural communities that actively use forest resources. In Albania, there is an increase in demand for ecotourism, especially in mountainous regions, where local communities organise agrotourism routes, tasting tours using local products, walks in forests and eco-farms. In the mountainous regions of Leja and Kukes, the average annual income of local farms from ecotourism by 2018 was USD 6,000, while in 2023 this figure increased to USD 7,500-8,000, which indicates a 25-30% increase.

Thus, the integration of forestry and agricultural practices not only increases the profitability of agriculture, but also creates a sustainable economic base for the development of local communities, reducing their dependence on traditional agriculture. Investments in agroforestry contribute to the development of long-term economic benefits by increasing land productivity, more efficient use of natural resources and the development of new economic activities, in particular ecotourism. Despite significant environmental and economic benefits, the integration of forestry and agricultural practices in Albania faces a number of barriers that limit its widespread implementation. The main challenges are related to financial, legal, technological, and social factors that affect the effectiveness of agroforestry development.

One of the key constraints is financial instability and limited investment in forest agrarian systems. Despite international initiatives such as the United Nations Development Programme (2024) and the Global Environment Facility, which are aimed at supporting sustainable land use, the lack of government subsidies and low lending to farmers and forest enterprises make it difficult to adapt agroforestry methods. The high initial costs of creating mixed forest systems, the need for a long payback period, and limited financial incentives create significant barriers for small and medium-sized forest users. In addition, the lack of investment in the restoration of degraded forest areas limits the opportunities for the development of multifunctional forestry, which is important for improving the environmental sustainability of regions.

The second significant barrier is legal and regulatory restrictions. In the process of decentralising forest management, which began in 2015, local communities were granted the right to use forest land, but the legal status of many lands remains uncertain. The insufficient legislative framework for property rights and long-term use of natural resources makes it difficult to attract investment in forest restoration and the development of sustainable forest agrarian systems. In particular, the lack of clearly defined rules for the use of forests leads to their degradation due to poor use of resources, which reduces the ecosystem functions of forest areas.

Technological limitations also affect the pace of implementation of forest agrarian practices. The lack of scientifically based recommendations for adapting agroforestry to specific natural conditions in Albania, limited access to modern technologies for managing forest ecosystems, such as remote monitoring of the state of forest stands, the use of drones to assess biodiversity and analyse degradation processes, significantly reduce the effectiveness of these methods. The lack of specialised educational programmes and advisory support for forest users further complicates the integration of modern technologies into forestry.

A significant factor influencing the spread of agroforestry is the social perception and level of awareness of the local population about its advantages. Research shows that most forest owners and farmers prefer traditional farming methods because of a lack of understanding of the long-term environmental and economic benefits of implementing forest farming systems. The lack of organised cooperatives and support from local authorities contributes to the preservation of conservative approaches to forest management.

An additional challenge is the impact of climate change, which is already having significant implications for Albania's forest ecosystems. It is predicted that by 2050, the average annual temperature in the country will increase by 1.3-2.2°C, which will be accompanied by a decrease in precipitation by 2.1-4.3% and an increase in the frequency of extreme weather events, such as droughts and heavy downpours. These changes can lead to degradation of forest ecosystems, increased risk of forest fires, loss of biodiversity, and reduced productivity of tree stands. Mountain forests are particularly vulnerable, where a violation of the water regime and an increase in the average annual temperature can lead to changes in the species composition of trees, a decrease in the area of moisture-loving forest ecosystems and an acceleration of soil erosion processes.

Increasing climate risks also affect forestry, increasing the need for adaptation strategies. In particular, it is necessary to develop reforestation programmes using drought-resistant and biodiversity-rich tree species, create protective forest belts to reduce the risk of erosion and land degradation, and introduce environmental monitoring systems to predict changes in forest ecosystems.

Thus, overcoming the challenges that hinder the integration of forestry and agricultural practices in Albania requires a comprehensive approach. The development of effective financial mechanisms for the restoration of forest resources, the improvement of the legal framework for rational forest management, the introduction of modern technologies for monitoring the state of forests and educational programmes for forest users and farmers are necessary steps to ensure the ecological sustainability of forest areas. Integrating these factors will help to reduce forest degradation, improve their ecosystem functions, and ensure long-term sustainable development in the region.

The integration of forestry and agriculture has significant potential for sustainable rural development in Albania. It is important not only to use agroforestry as a tool for increasing agricultural productivity, but also its role in preserving and restoring forest ecosystems. To achieve long-term efficiency, it is necessary to implement comprehensive measures aimed at forming a policy of integrated management of forests and agricultural landscapes, expanding financial support, introducing modern technologies in the forest sector, and improving the environmental sustainability of degraded territories.

In the future, the key task will be to develop a national strategy for the development of agroforestry, which will include measures to restore degraded forest landscapes and strengthen the ecosystem functions of forests. It is planned to create support programmes not only for farmers, but also for forest sector enterprises engaged in forest restoration, cultivation of multifunctional forest stands, and development of forest bioeconomics. Considering the experience of EU countries such as France and Germany, it is worth implementing financial mechanisms aimed at stimulating agroforestry in the context of forest conservation, in particular, through subsidies, tax incentives and, investments in expanding the area of mixed forests.

In addition to financial support, the development of the scientific and technological base for monitoring the state of forests, expanding the use of innovative forestry methods and improving the efficiency of forest ecosystem management will play a significant role. The creation of research centres to study the relationship between forestry and agroforestry will allow adapting forest models to the specific natural and climatic conditions of Albania. The use of the latest technologies, such as remote monitoring of forests, analysis of satellite data to assess the dynamics of changes in forest cover, development of water management systems in forest regions, will contribute to improving the ecological sustainability of forests.

The approach to integrated forest management and social responsibility of communities for the conservation of forest resources play a significant role in the development of agroforestry. The expansion of the network of forest cooperatives will contribute to the efficient use of natural resources and the creation of local economic initiatives in the forest sector. An important area will also be the involvement of the local population in forest restoration programmes and the development of multifunctional forest ecosystems, which will create additional employment opportunities and increase the income of forest communities.

Special attention should be paid to environmental aspects. It is expected that the introduction of agroforestry will contribute to the restoration of degraded forest ecosystems and improve their ecological functions. Restoration of forests in arid regions will help to stabilise the microclimate, reduce erosion processes, and increase the level of carbon conservation in soils. It is predicted that over the next decade, forest areas that have been partially degraded due to intensive farming and overgrazing can be restored by 15-20% due to the introduction of mixed agroforestry systems.

In addition to increasing farmers' incomes, the introduction of agroforestry will create economic benefits for the forest industry. In particular, the wood supply will increase due to the expansion of the area of multifunctional forest stands, which will contribute to the development of forest bioeconomics and the creation of new sources of income through the processing of wood raw materials. It is also possible to reduce the cost of reforestation through natural mechanisms of forest regeneration in mixed systems. As a result, the share of wood produced under sustainable forestry can grow by 10-15%, which will contribute to the development of the market for environmentally certified wood and reduce dependence on imports of forest products.

Due to these steps, the share of agroforestry can grow to 25% of the total area of agricultural land over the next decade, which will have a positive impact on the state of forests. It is expected to increase the area of restored forest ecosystems, which will help to reduce the level of forest degradation by 30-40% and improve biodiversity in regions that are currently under environmental pressure. The integrated implementation of these measures will contribute to economic growth and environmental stability, adaptation to climate change and sustainable development of Albania's forest areas.

Discussion

The results of the study confirm the importance of integrating forestry and agricultural practices for the sustainable development of rural areas in Albania. It was established that the use of agroforestry systems contributes to increasing land productivity, reducing erosion processes and improving the economic well-being of local communities. The findings are consistent with previous studies that focus on the need for an integrated approach to agricultural development in the face of current environmental challenges.

It was confirmed that rural development requires integrated strategies that cover environmental, social, and economic aspects. Analysis of sustainable rural development policies within the Smart Village concept presented in the study by M. Osmani (2023) emphasises the need for digital technologies and effective management of natural resources to improve the standard of living in rural communities. The introduction of agroforestry corresponds to these approaches, since it involves optimising land use, reducing the environmental burden and developing cost-effective management models. The study showed that financial support for farmers is a critical factor for the large-scale implementation of agroforestry systems. The lack of financial incentives, subsidies and public funding programmes remains one of the main obstacles to the development of this area. The study by P. Ymeri (2022) emphasises that insufficient state support and lack of financial incentives significantly slow down the transition to sustainable land use, especially in the countries of the Balkan region.

The issue of land consolidation also plays a significant role in improving the efficiency of agriculture and the use of natural resources (Zorin, 2024). According to the analysis by F. Sallaku *et al*. (2010), land consolidation contributes to the rational use of territories, which is especially important for the introduction of agroforestry systems. Albania is experiencing significant land fragmentation, which makes it difficult to integrate forest practices into agricultural production. The results of the study confirm that combining land resources within cooperative management can help improve the efficiency of agroforestry systems. Social aspects of agroforestry development also remain an important factor. As indicated by D. Shehu *et al*. (2013), low awareness of local communities about the long-term economic and environmental benefits of agroforestry remains a significant barrier to its development. Similar trends can be seen in Albania, where a significant proportion of farmers adhere to traditional management methods, which limits the introduction of integrated approaches to natural resource management.

From the standpoint of environmental sustainability, the results of the study confirm the conclusions of S. Fatima *et al*. (2024) on the positive impact of sustainable forestry on soil health, biodiversity, and climate change adaptation. Agroforestry helps to increase the level of organic matter in soils, reduce wind and water erosion, and improve the water balance in agroecosystems (Muminova *et al*., 2023). It is important that the introduction of agroforestry systems can play a significant role in mitigating the effects of climate change already observed in the region. In an international context, the development of agroforestry can be linked to general trends in forest sector reform in developing countries (Belmega *et al*., 2024). The study by E.K. Nambiar (2021) on Vietnam demonstrates that integrating forestry into agricultural production can significantly increase productivity, ensure farmers' access to fair markets, and promote economic growth in rural communities. A similar approach can be applied in Albania through the introduction of cooperative models for forestry and agricultural resources management.

The results are consistent with conclusions of A. Raihan *et al*. (2024) on the importance of combining economic growth, energy innovation, and sustainable natural resource management to reduce greenhouse gas emissions. The introduction of agroforestry in Albania can help to reduce the carbon footprint of the agricultural sector, which meets European environmental standards. One of the key aspects of sustainable development is the integration of educational, managerial, and environmental strategies into rural development. As indicated by Y. Yu *et al*. (2024), education and competence development among the local population are important factors for the successful implementation of sustainable practices. Insufficient awareness and access to modern farming practices remains one of the main obstacles to the expansion of agroforestry. The results of this study confirm that increasing the level of knowledge of farmers through educational initiatives and information campaigns will contribute to more active implementation of agroforestry systems.

The development of agroforestry is also part of a broader process of restoring multifunctional cultural landscapes that combine traditional farming methods and modern innovative approaches (Drobitko & Alakbarov, 2023; Moroz, 2024). S. Wang (2004) emphasised that the concept of sustainable forest management can have different interpretations depending on the economic, social, and environmental context. The analysis carried out in this study confirmed that in the case of Albania, sustainable forest development largely depends on the integration of forestry and agricultural practices. In contrast to the general approach of S. Wang, the results obtained were aimed at specific mechanisms of adaptation of agroforestry to the natural and climatic conditions of the country. The study by J. Gupta *et al*. (2022) emphasises the importance of agroforestry waste management to improve the environmental efficiency of agriculture. In Albania, the possibility of using biomass derived from agroforestry systems can contribute to the development of renewable energy and reduce carbon emissions (Shumka *et al*., 2021). From the standpoint of macroeconomic trends, the integration of forestry into agricultural production corresponds to global approaches to a green economy. The study by M. Riviere *et al*. (2020) considered the evolution of integrated economic models used in the forest sector and their adaptation to new environmental and market conditions. The study confirmed the need to develop economic models that consider the relationship between forestry and agricultural systems.

Agroforestry is also seen as part of a climate change adaptation strategy. The study by D. Ntawuruhunga *et al*. (2023) confirms that adaptive agroforestry systems can help to preserve soil moisture, reduce erosion, and increase the resilience of agricultural landscapes to climate change. In Albania, the expected increase in average temperatures and reduced precipitation by 2050 requires the development of effective water management methods, which can be achieved through the introduction of protective forest belts and the use of perennials in agricultural systems. The analysis of the regional policy of sustainable development confirms that the successful implementation of agroforestry is possible only under the conditions of an effective territorial policy. T. Schulz *et al*. (2023) analysed trade-offs and conflicts between economic development and sustainable forest management. The study also confirmed the existence of contradictions between economic interests and environmental priorities, in particular in the financing of forest restoration programmes. The lack of agreed financial mechanisms and land-use disputes identified in this study reflect the general trends described by the researcher, in particular, difficulties in implementing policies that combine economic growth with the conservation of natural resources.

Special attention should be paid to social factors affecting the development of agroforestry. As noted in the study by S. Gatama *et al*. (2024), issues of gender equality and the involvement of various social groups in the management of natural resources are important for ensuring sustainable development. In the case of Albania, the establishment of cooperative forms of forest management can help to increase social cohesion and involve local communities in decision-making on the use of forest resources. The study by P. Datta *et al*. (2024) demonstrates that the interaction between agroforestry, animal husbandry, and agriculture in Bangladesh can increase land productivity and promote sustainable management of natural resources. A similar approach can be applied in Albania, where the integration of animal husbandry and agroforestry, in particular, in the form of forest-pastoral systems, helps to reduce farmers' feed costs and maintain biodiversity.

The analysis showed a significant impact of agroforestry on the ecological sustainability of forest ecosystems and their economic prospects in Albania. M. Sotirov *et al*. (2015) considered the integration of forest policy in the European context, where special attention was paid to coordinating strategies for sustainable forest management and their multifunctional use. The problems identified in this study, in particular, the uncertainty of land status and the lack of financial support mechanisms, partially coincide with the conclusions of M. Sotirov *et al*. on barriers to the implementation of integrated forest management. However, the current study focused on local aspects, while the European study covered a broader regional scale.

The analysis of economic opportunities for forestry development in Albania has certain parallels with the conclusions of J. Arce (2019). The researcher emphasised the importance of forests as a driver of sustainable economic growth and job creation. The study also confirmed that the development of forest cooperatives and the integration of forest land into regional economic processes contribute to increasing employment and income diversification in rural areas. The difference was that the global analysis by J. Arce considered the overall economic role of forests, while this study specified ways to implement financial mechanisms for the development of agroforestry.

Considerable attention in modern research is paid to the use of digital technologies for monitoring the state of forests. A. Kafy *et al*. (2023) proved that the use of satellite data and remote sensing allows more effectively assessing changes in forest cover and carbon storage. Although the technological aspects were considered in less detail in this study, it was found that the lack of monitoring systems makes it difficult to manage natural resources. The findings confirm the need to implement digital solutions in the field of forestry, which is consistent with the opinion of A. Kafy *et al*. on the importance of geoinformation technologies in the conservation of forest ecosystems.

The importance of forests in combating climate change was a central issue in the study by A. Raihan (2023a). The researcher investigated the role of forest ecosystems in reducing greenhouse gas emissions and the impact of environmentally oriented practices on the carbon balance. The results of the analysis confirmed that agroforestry contributes to the accumulation of carbon in forest soils, and reduces the level of erosion, which is a critical factor in the context of climate change mitigation.

The economic aspects of forest management were the subject of a separate study by A. Raihan (2023b), where financial support mechanisms for sustainable forest management were considered. This study confirmed that the lack of subsidies and concessional lending creates significant obstacles to the expansion of agroforestry systems. The conclusions regarding economic constraints coincide with the results of A. Raihan, who stressed the need to use market mechanisms to finance forest conservation activities.

Thus, the results of the study confirm the need for an integrated approach to the development of agroforestry in Albania, including financial incentives, development of educational initiatives, effective land management, and adaptation to climate change. The alignment of these factors with international practices will contribute to the creation of a sustainable and cost-effective agricultural system that meets the current challenges of sustainable development.

Conclusions

The study confirmed that the development of agroforestry in Albania is a key area for improving the sustainability of forest ecosystems, their restoration, and improving forest resource management. The integration of forestry practices with agriculture contributes to the conservation of biodiversity, improving the microclimate, and reducing the risks of degradation of natural landscapes. It was studied that the area of forest land in the country is approximately 1.05 million hectares, of which a significant part was negatively affected due to overgrazing, irrational land use, and climate change.

The results of the study show that the spread of mixed agroforestry systems can increase the ecological stability of forest ecosystems. In particular, the restoration of degraded woodlands through the combination of tree stands and grazing contributes to the natural restoration of forest floor and stabilisation of soil moisture levels. Forest-pastoral systems reduce fire hazards by controlling excess vegetation, and improve soil quality by accumulating organic matter. It was determined that protective forest belts play an important role in preventing erosion processes and restoring forest landscapes. The analysis showed that the use of these systems helps to reduce soil erosion by 30-40% and stabilise the microclimate, which is critical for forest ecosystems in mountainous areas. Forestry and mixed forest systems have also been shown to improve soil quality and contribute to increased carbon reserves, which is important in the context of climate change mitigation.

It was predicted that by 2050, under the influence of climate change, forest ecosystems in Albania may undergo a significant transformation: an increase in the average annual temperature by 1.3-2.2°C and a decrease in precipitation by 2.1-4.3% may lead to degradation of mountain forests and a reduction in the area of moisture-loving forest formations. In this regard, the conservation of existing woodlands, the introduction of natural forest renewal programmes, and the integration of adaptive management methods, such as the use of drought-tolerant tree species and the creation of forest buffer zones to protect water resources, are important measures. The main limitation of agroforestry development remains the lack of financial mechanisms aimed at supporting sustainable forest management. The lack of government subsidies and limited access to credit make it difficult to restore forest ecosystems, especially in regions with high levels of degradation. The study also identified shortcomings in the legislative framework: uncertainty of ownership rights to forest land and poor efficiency of local management hinder long-term planning of forest restoration measures.

The results suggest the establishment of national forest restoration support programmes, which will include financial incentives for farmers and forest users implementing mixed forest systems. Important measures include the introduction of remote monitoring of the state of forests, the expansion of the network of forest cooperatives, and the creation of programmes for the protection of mountain forest regions. For further research, it is advisable to focus on assessing the impact of various agroforestry models on the productivity of forest ecosystems and the effectiveness of financial incentives for forest restoration. In particular, it is necessary to explore the possibilities of implementing environmental certification systems for wood and assess the potential for the development of forest bioeconomics as a mechanism for promoting sustainable forest management.

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Conflict of Interest

None.

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Лісове господарство та розвиток сільських територій в Албанії: інтеграція лісового та сільського господарства для сталого майбутнього в економіці

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Анотація. Інтеграція лісогосподарських та сільськогосподарських практик сприяє екологічній стійкості та економічному розвитку сільських територій, особливо в регіонах з деградацією ґрунтів. Метою дослідження було оцінити вплив систем агролісомеліорації на продуктивність земель, збереження природних ресурсів та соціально-економічний розвиток місцевих громад; виявити бар'єри та перспективи їх подальшого впровадження.

Методологія дослідження включала статистичний аналіз, порівняння ефективності різних моделей агролісомеліорації, оцінку економічних та екологічних показників. Дослідження показало, що площа земель, залучених до агролісомеліорації, становить 150-200 тис. га (10 % сільськогосподарських угідь). Лісові та пасовищні системи зменшили витрати фермерів на корми на 20-25 %, а використання змішаних моделей агролісомеліорації підвищило врожайність сільськогосподарських культур на 14% порівняно з традиційним землеробством. Встановлено, що рівень органічної речовини в ґрунтах таких систем майже вдвічі вищий, ніж у традиційних сільськогосподарських ландшафтах, а ерозійні процеси зменшуються на 20-30 %. Лісові насадження в рамках агролісомеліорації сприяють збереженню біорізноманіття, зокрема, збільшенню кількості корисних комах-запилювачів на 40 %, відновленню популяцій дрібних ссавців і птахів. Також було виявлено, що децентралізація управління лісовим господарством призвела до створення понад 60 лісових кооперативів, які забезпечують ефективне управління лісовими ресурсами та підвищують економічну стійкість місцевих громад. Виявлено, що основними перешкодами для розвитку агролісомеліорації в Албанії є відсутність державної підтримки, фінансові обмеження, технологічні прогалини та низька обізнаність фермерів. Результати дослідження вказують на необхідність створення фінансових стимулів, розвитку лісових кооперативів, поширення інноваційних технологій та розширення інформаційної підтримки фермерів. Практичне значення дослідження полягає у розробці комплексної стратегії сталого розвитку сільського господарства, яка сприятиме підвищенню продуктивності земель, економічній стабільності місцевих громад та адаптації до зміни клімату

Ключові слова: сталий розвиток; ерозія ґрунтів; агролісомеліорація; екологічна стійкість; продуктивність земель; економічна адаптація

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The impact of combat actions on forest ecosystems: Challenges for environmental, national security and state resilience

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Abstract. This study aimed to analyse the impact of active military actions on biodiversity and forest resources. The research employed the following methods: analysis of satellite data from open sources and media reports, as well as methods of generalisation and systematisation. It was established that the accumulation of dry biomass following fires has contributed to the spread

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of wildfires. The formation of crater-like depressions due to explosions altered the composition of forest stands and the water balance, affecting the region's water supply and leading to either waterlogging or desiccation. The study's findings indicated that in 2024, following shelling in a forested area near the village of Buda-Babynetska in the Kyiv Region, the forest cover within a 25-metre radius was destroyed. This included plant species such as Scots pine (*Pinus sylvestris*), pedunculate oak (*Quercus robur*), and silver birch (*Betula pendula*). The analysis of information from open sources and media reports demonstrated that ruderal species, such as common ragweed (*Ambrosia artemisiifolia* L.) and black locust (*Robinia pseudoacacia* L.), had colonised damaged areas. This indicated active vegetation establishment by species capable of rapid recovery following disturbances. In explosion crater zones, revegetation processes progressed slowly. For instance, in one of the craters within Hetmanskyi National Natural Park in Sumy Region, only a few specimens of ragweed and black locust were recorded, while another crater remained devoid of any vegetation. To facilitate forest restoration in Ukraine following the cessation of active hostilities, the application of mycorrhizal fungi, the use of container-grown seedlings, and hydroseeding were recommended. The findings on the condition of forested areas may contribute to the development of strategies for the conservation and restoration of fire-damaged forest ecosystems

Keywords: fires; craters; invasions; ruderal plant species; biodiversity; vegetation cover

Introduction

One of the primary ecological challenges facing Ukraine has been the destruction of forests through fires. Forest ecosystems in Ukraine play a vital role in climate regulation and biodiversity conservation. The destruction of forests by fires has degraded soil and water resources, posing a threat to the existence of many species. The relevance of this research stems from the fact that one of the key ecological and economic problems is the environmental pollution of Ukraine due to the military actions of the Russian occupying forces. The loss of forest areas through fires, particularly those caused by shelling and the use of military equipment, has had catastrophic consequences for environmental quality. The disruption of carbon absorption, water cycle maintenance, and the destruction of habitats for many flora and fauna species through fires have led to soil degradation, reduced water resource quality, and threats to biodiversity, resulting in long-term impacts on ecosystems (Fedoniuk *et al.*, 2024). The concentration of various pollution sources in occupied settlements is very high. Without comprehensive research into the effects of forest fires, risks to ecosystems and society may arise, as the degradation of forest ecosystems directly affects climate regulation, biodiversity, and the quality of life for the population. Specifically, without proper attention to forest restoration, ecosystems will be unable to perform their natural climate and water resource regulation functions, leading to further environmental degradation and increased negative impacts on public health. Therefore, the importance of this research lies not only in nature conservation but also in ensuring the long-term stability of ecosystems and preserving life-supporting functions for society.

The research problem focused on the fact that the impact of the Russian-Ukrainian war has contributed to an increase in the area of forests affected by fire. According to an investigation by journalists from NGL.media, "To cut it all", during the full-scale Russian invasion of Ukraine (February 2022 to April 2024), over 60,000 hectares of forest in temporarily occupied Ukrainian territories were permanently destroyed (Verbovska & Tuziak, 2024). The existence of this problem was confirmed by the fact that the introduction of toxic substances into the soil due to bombardments and the use of chemical agents for military purposes resulted in significant ecosystem pollution. The excessive concentration of heavy metals has deteriorated the physicochemical properties of the soil, reduced its fertility and hindered normal plant growth.

The issue of forest stand damage due to post-combat fires was particularly acute in the Luhansk Region, where 16,500 hectares of forests were damaged between February 2022 and April 2022. The issue was investigated by O.V. Kratko & S.V. Kratko (2023). Their research demonstrated that explosions and bombardments, as well as forest and steppe fires in the Luhansk, Zhytomyr, Kyiv, Kherson, Chernihiv, and Poltava regions, led to a reduction in biodiversity within protected natural areas and disrupted forest ecosystems.

A pressing problem was the necessity to conduct statistical analysis and forecast the condition of forest resources in Ukrainian regions, particularly in the Lviv and Kharkiv regions. Research in this area was undertaken by E. Korotetska *et al*. (2022). The findings of these scientists revealed a significant difference in the state of forests between the two regions. Specifically, the forest stands in the Kharkiv Region were found to be in a worse condition compared to the forests of the Lviv Region, which is attributed to the high number of fires.

Concurrently, the study of ecological aspects of forest restoration in anthropogenically degraded areas has been an important topic for contemporary ecologists. In their research, V.B. Levchenko & T.S. Ganzhaliuk (2022) proposed an innovative technology for growing forest seedlings with a closed root system, which significantly increased their survival rate after forest fires. This research demonstrated the importance of improving reforestation methods to prevent further ecosystem degradation.

Particular attention was drawn to the increased risk of forest fires due to combat actions and mine laying, as investigated by Y.M. Senchikhin (2022). The author showed that the highest number of fires in Ukraine (2,381 cases) was recorded in March 2022, resulting in damage to 748,116 hectares of forests, with the Kherson and Kharkiv regions and the Chornobyl zone being the most affected. The study of these data highlighted the importance of developing new approaches to the prevention and control of forest fires in conflict conditions.

The issue of mechanical and fire damage to forest lands in the Zhytomyr Region has become particularly acute due to the ongoing military actions since February 2022. According to research by I. Patsev *et al*. (2023), approximately 120,000 hectares of forest were destroyed in the region, which negatively impacted the ecological state of forest ecosystems. The significant environmental damage inflicted on the forests of the Zhytomyr Region by combat actions underscores the urgent need for forest ecosystem restoration and the implementation of new forest management methods in wartime conditions.

The study of the problem of pine mistletoe infestation on the growth of pine trees has been relevant in current conditions. O.E. Sakici *et al*. (2023) recommended developing strategies aimed at reducing infection levels, such as the timely removal of infected trees and the implementation of preventive measures to reduce the spread of mistletoe in the future. The recommended approaches are important directions for preserving the health of forest ecosystems and enhancing their resistance to diseases and pests.

The issue of forest fire management remains relevant in the context of climate change and increasing human activity, as demonstrated in the research of A.P. Singh (2024). Given climate change and intensified human activities, the development of effective national and regional strategies for the prevention, suppression, and restoration of forest ecosystems is crucial for preserving the natural environment.

In 2024, insufficient attention has been paid to a comprehensive approach to studying the long-term effects of combat actions, deforestation, fires, and pollution on forest ecosystems, their restoration, and their resilience to further changes. This research aimed to analyse the negative factors during combat actions that cause damage to forest ecosystems, as well as to identify the main strategies for mitigating the consequences and measures for post-war restoration. The study's objectives included analysing the impact of military actions on forest ecosystems, identifying the main factors of forest damage resulting from combat actions, and developing recommendations for forest restoration in Ukraine after the end of active hostilities.

Materials and Methods

The study employed methods to assess the ecological state of forest ecosystems and analyse degradation processes resulting from military actions, as established by legislative acts: the State Standard of Ukraine No. ISO 14001:2015 "Environmental management systems. Requirements and guidelines for use" (2015), the Convention on Biological Diversity (1992), and the Forest Code of Ukraine (1994).

The study utilised the method of analysing satellite data from open sources and media to identify the main ecological consequences of military actions on forest ecosystems, collect and systematise facts about soil and water resource pollution, and analyse the impact of explosives and fires on vegetation and biodiversity. The method of generalisation and systematisation was used to form a comprehensive assessment of ecological changes in forests caused by combat actions, to structure information on negative impact factors and their consequences, and to develop conclusions about long-term ecological risks and possible pathways for forest ecosystem restoration.

Satellite data was obtained from open sources, such as official satellite imagery platforms and scientific publications, as well as from the commercial satellite company Planet Labs, which provided access to high spatial and spectral resolution satellite imagery (3 m/pixel) captured by the PlanetScope satellite system. These images are designed for detailed monitoring of localised damage, including crater formation and vegetation cover degradation.

Research on the effects of explosions and fires was conducted throughout 2024 in the Hetmanskyi National Natural Park in the Sumy Region and the forested area near the village of Buda-Babynetska in the Kyiv Region. The study of the impact of military actions on forest massifs was carried out in four areas located in the Sumy, Kyiv, Chernihiv, and Luhansk regions of Ukraine, as these territories were the most severely affected by military actions. A separate survey was conducted in the Zalissia National Natural Park (Hoholivski Hai tract), located on the border of the Kyiv and Chernihiv regions. Studies were conducted in damaged pine forest areas, assessing ruderal and adventive vegetation cover, analysing the herbaceous layer, and assessing the degree of forest stand damage after combat actions. These territories recorded instances of forest fires, explosions, mechanical destruction of forests by military equipment, and toxic substance contamination.

All sites were examined for mechanical damage and soil contamination. Soil samples were collected from horizons 0-10 cm, 10-30 cm, and 30-50 cm to assess changes in different layers. In each study area, 3-5 replicated test plots measuring 10 × 10 m were established.

From each plot, 5-point samples were collected and then mixed to obtain an average sample weighing 500 g. These methods were used because collecting soil samples at different depths allowed for the assessment of the contamination level and its vertical migration.

Archival data that could allow for the assessment of changes in forest conditions before and after military actions are limited, so the comparison of forest conditions was based on the analysis of open sources, field observations, and expert assessments (Almost 19 thousand..., 2024; As a result..., 2024; Examination of a..., 2024; Marchan, 2025).

Cartographic work was also conducted to determine the boundaries of damaged areas and estimate the extent of forest cover changes. The condition of the vegetation cover was assessed using descriptive and quantitative methods. It was determined which plant species had recovered after explosions, fires, and other damage. Changes in vegetation composition were monitored using square quadrats, which allowed for the determination of the percentage coverage of the area by herbaceous and shrub vegetation. The spread of ruderal species, such as common ragweed (*Ambrosia artemisiifolia*) and black locust (*Robinia pseudoacacia*), in explosion sites was assessed.

Results

The war has had a profoundly negative impact on forest ecosystems. Forests have been used as natural cover for military equipment and personnel and have been subjected to armed shelling, resulting in extensive damage. Shelling from various types of weapons has led to the destruction of trees, soil degradation, chemical contamination, and loss of biodiversity. Furthermore, explosions and fires have disrupted the ecological balance, altering the composition of forest stands and causing long-term environmental consequences. Specifically, there has been a mass die-off of trees, which in turn has led to the replacement of native species with less resilient ones. Explosion craters have formed, and mechanical destruction of soil has occurred due to the digging of trenches and fortifications by military equipment. Soils and groundwater have been contaminated with ammunition residues, fuels and lubricants (petrol, liquefied natural gas, and motor oils), heavy metals, and toxic chemicals. Explosions, fires, and mechanical damage have resulted in the death of animals and plants, leading to forced fauna migration.

When trees are damaged or completely destroyed, and dry biomass accumulates, forest fires spread more easily. Explosions create crater-like depressions in the ground and disrupt vegetation cover, altering the water balance of forests and leading to either waterlogging or drying out of forest areas. This reduces the water supply to the forest, as natural vegetation layers that help retain moisture in the soil are lost. Such changes result in faster soil drying and an increased risk of erosion. The accumulation of dry biomass after fires further promotes the spread of fire, which also has consequences for the water balance. After such fires, the ground surface loses its ability to retain moisture as organic residue layers are burned, and elevated temperatures dry out the soil. If these processes create craters or significant damage to vegetation cover, it encourages water accumulation in lower parts of the terrain, creating conditions for rising groundwater levels.

According to the Northern Forestry Office, 25 fires occurred in the Chernihiv Region in 2024, caused by artillery shelling, shell explosions, and the fall of rocket and drone fragments (Marchan, 2025). These fires affected 93.71 hectares of forest areas in the Chernihiv Region. In total, 151 fires occurred in the Sumy and Chernihiv regions due to military actions in 2024, resulting in damage to more than 427 hectares of forest. According to reports from the Rubizhne City Military Administration website and materials provided by the Sievierodonetsk City Environmental Association Green World and the human rights organisation "Environment. People. Law", as of 2022 (no new data is available due to the occupation of the region by Russian troops), 28,000 hectares of forests, predominantly coniferous, were damaged during combat actions in the Luhansk Region. According to the press service of the Kyiv City State Administration, it is known that since the beginning of the full-scale military actions in 2022-2024, over 1,300 trees have been damaged in the Sviatoshyn Forest Park Enterprise and 0.5 hectares of forest areas in the Darnytsia Forest Park Enterprise (As a result..., 2024).

According to materials provided by the Ukrainian National News Agency Ukrinform, as of 2024, 18,500 hectares of forests in the Sumy and Chernihiv regions remain mined (Almost 19 thousand..., 2024). Following de-occupation, 16,600 hectares of forests were cleared of mines in 8 branches of the state enterprise "Forests of Ukraine", 5 of which are in the Sumy Region and 3 in the Chernihiv Region, while another 18,500 hectares require demining. The largest area of demined forests was in the Chernihiv branch of state enterprise "Forests of Ukraine" with 9,500 hectares. The territory under the jurisdiction of the Konotop branch of state enterprise "Forests of Ukraine," covering more than 6,700 hectares, remains the most potentially contaminated with explosive ordnance. L. Shumilo *et al*. (2023) reported that in the temporarily occupied territories of the Luhansk Region, approximately 8,600 hectares of forest were lost due to illegal logging and other actions by the occupiers between 2014 and 2020 (no new data is available due to the occupation of the region by Russian troops). According to information provided by experts from the society organisation Ecoaction, as of 2023, 126,000 hectares of forests in the Kyiv Region were damaged by combat actions, fires, and explosions of ammunition (As a result..., 2024). It is worth noting that a complete assessment of biodiversity losses, including the decline of certain animal populations, requires further research and monitoring, as many areas remain dangerous or inaccessible for detailed surveys.

The products of combustion and explosions (nitrogen oxides (NO_2), carbon monoxide (CO), heavy metals – lead (Pb), cadmium (Cd), mercury (Hg), uranium (U)) persist in the environment for extended periods, causing deterioration in air quality and plant health. Nitrogen oxides accumulate in plants, where they are converted into nitrates. Elevated concentrations of nitrate compounds (NO_3^-), particularly sodium, calcium, and ammonium nitrates, have a toxic effect on plant stands, disrupting normal metabolism. Nitrogen oxides negatively impact plant chlorophyll, reducing the efficiency of photosynthesis, which leads to decreased energy production and slowed plant growth. The release of nitrogen oxides generates free radicals that damage plant cells, including cell membranes, proteins, and DNA. The increased soil acidity caused by acid rain makes heavy metals in soil layers more soluble and capable of penetrating deeper soil layers and aquifers. This can lead to groundwater contamination with heavy metals. Specifically, excessive lead concentrations in water can be toxic to humans who consume the water; high cadmium content can impair kidney function and cause other serious health problems; and copper and zinc in high concentrations can cause intoxication and water quality degradation. Table 1 presents data on heavy metal contamination of soils under forest stands at various depths in damaged forest areas.

Table 1. Heavy metal contamination of soils under forest stands at various depths in damaged forest areas

Forest area	Depth, cm	Pb, mg/kg	Cd, mg/kg	Hg, mg/kg	U, mg/kg	Soil pH	Forest stand composition
Buda-Babynetska	0-10	85	1.2	0.15	2.3	5.2	Scots pine (*Pinus sylvestris*), pedunculate oak (*Quercus robur*)
	10-30	54	0.8	0.09	1.7	5.5	
	30-50	22	0.4	0.05	1.1	5.8	
Hetmanskyi National Natural Park, Crater No. 1	0-10	97	1.5	0.18	2.7	5.1	Pedunculate oak (*Quercus robur*), silver birch (*Betula pendula*)
	10-30	63	0.9	0.12	1.9	5.4	
	30-50	27	0.5	0.06	1.3	5.7	

Source: created by the authors

The analysis of the obtained data on heavy metal contamination in damaged forest soils revealed the following patterns: in all studied forest areas, the concentrations of Pb, Cd, Hg, and U were higher in the upper (0-10 cm) soil layer and gradually decreased with depth. These data are consistent with the processes of migration and accumulation of pollutants in surface layers due to atmospheric precipitation, biological absorption, and the limited mobility of heavy metals in the soil. The highest levels of contamination were recorded in Crater No. 1 of the Hetmanskyi National Natural Park, which could indicate more intense anthropogenic pressure or specific soil characteristics. In the Buda-Babynetska forest area, slightly lower levels of Pb, Cd, Hg, and U were observed, but they still indicate significant contamination. In the upper soil layer, the pH was lower (5.1-5.2), which could contribute to greater heavy metal mobility. With increasing depth, the pH increased (up to 5.8), which could reduce heavy metal availability due to the formation of less soluble compounds. Areas covered with pedunculate oak, silver birch, and Scots pine may have varying degrees of influence on heavy metal migration due to differences in root systems and litter properties. For example, oak might promote greater heavy metal accumulation in the litter layer, while pine might result in less leaching of metals into deeper layers.

High levels of carbon monoxide have altered the concentration of chlorophyll in plants, reducing their ability to transport oxygen and limiting oxygen access to plant tissues, thereby impairing respiration and reducing photosynthetic efficiency. The decrease in photosynthetic efficiency and the increase in gas exchange disturbances in plants has led to a loss of soil fertility and a reduction in agricultural crop productivity, which in turn has affected yields. Although CO itself is not highly aggressive to plant tissues, it can interact with other air pollutants, such as ozone or sulphur dioxide, to form toxic compounds that damage plant cells and the tissues of roots, stems, and leaves.

Lead accumulates in the roots, stems, and leaves of plants, disrupting normal water and nutrient absorption and causing a reduction in plant growth and development. Lead can inhibit the activity of essential enzymes, such as catalase, peroxidase, and other antioxidant enzymes, causing disruptions in metabolic processes, including water balance and photosynthetic functions. This toxic metal disrupts the transport of vital ions (calcium, magnesium, and potassium) across cell membranes, affecting the plant's electrolyte balance and its ability to maintain normal water pressure levels within cells. Lead can also hinder seed germination and root growth, limiting the plant's ability to develop and adapt normally in contaminated environments. Additionally, by affecting the DNA structure of plants, it can lead to mutations and disruptions in replication and transcription mechanisms, ultimately impacting plant reproduction and survival.

Cadmium readily penetrates plants, accumulating in tissues and causing toxic effects such as the disruption of cellular metabolism of essential minerals like calcium, magnesium, and potassium, and a reduction in protein synthesis, leading to impaired enzyme system function. This results in decreased growth, plant vitality, and a reduction in their vitamin content. Cadmium reduces chlorophyll activity, disrupting photosynthesis processes through damage to chloroplasts and decreased energy production for metabolic processes. It induces oxidative stress, leading to the formation of free radicals that can damage lipid cell membranes, disrupting their integrity and function. Cadmium can replace essential elements, such as calcium (Ca), magnesium (Mg), and potassium (K), in plant cells, leading to disruptions in various biochemical processes and even halting growth.

Mercury, which settles in the stem and root parts of plants, reduces their photosynthetic capacity and induces oxidative stress. Mercury can be toxic to cells, damaging membranes and DNA, which leads to disruptions in plant growth and development. Gradually, mercury can accumulate in soil and water, potentially contaminating water resources and food chains, and negatively affecting animals and humans.

Mercury can inhibit the activity of enzymes involved in photosynthetic processes, such as ribulose-1,5-bisphosphate carboxylase/oxygenase (RuBisCO). This results in a decrease in photosynthetic activity, reducing the amount of organic matter produced and lowering plant productivity. An important function of RuBisCO is carboxylation. RuBisCO adds a molecule of carbon dioxide (CO_2) to ribulose1,5bisphosphate, a five-carbon sugar, resulting in the formation of two molecules of 3-phosphoglycerate. This step is the first stage in carbon fixation and organic compound synthesis. RuBisCO also performs oxygenation. RuBisCO can bind oxygen (O_2) instead of CO_2, leading to a process called photorespiration. Photorespiration is less efficient than photosynthesis because it reduces plant productivity by consuming energy for processes that do not result in the synthesis of organic compounds.

As uranium is a toxic element for the root system, it causes changes in its structure and function, which disrupts water and nutrient absorption and slows down overall plant growth. High concentrations of uranium can lead to the oxidation of cellular components, impairing their function and reducing photosynthetic efficiency, which in turn decreases the production of organic compounds. Uranium is a radioactive element, so its accumulation in plants leads to radiation exposure of cells. This causes mutations at the genetic level, affecting the reproductive capacity of plants and reducing their resistance to stress factors. This heavy metal affects soil acidity, altering its chemical composition and the availability of micronutrients to plants. This leads to a deficiency of essential growth elements such as calcium, magnesium, and phosphorus. The toxic metal can alter soil microbial activity, which in turn reduces the availability of nutrients for plants and their ability to resist diseases and stress. The disruption of water-regulating, soil-protecting, climateregulating, and sanitary-hygienic functions of forests has negatively impacted local and global climates.

The long-term impact of heavy metal contamination on ecosystems, particularly groundwater, can have serious consequences, including for human health. Heavy metals, such as cadmium, mercury, lead, copper, and others, can penetrate soil and groundwater as a result of industrial emissions, agricultural practices (e.g., the use of pesticides and fertilisers), or the aftermath of forest fires, which contribute to the release of pollutants from soils. Once in the soil, heavy metals can accumulate in various soil horizons, including aquifers, and gradually migrate into groundwater. As groundwater is often used for drinking water supplies, heavy metal contamination can lead to a deterioration in water quality, posing serious risks to public health. The toxicity of mercury, cadmium, and lead can lead to chronic diseases, including kidney and nervous system disorders, as well as an increased risk of cancer.

Analysis of information from open sources has identified the following key factors that have impacted forest ecosystems during combat actions: damaged and destroyed trees due to explosions, fires, and the passage of military equipment; accumulated heavy metals, explosive residues, fuel, and other toxic substances; detonation of munitions and ignition of military vehicles; the spread of pests and tree diseases; restricted access to forest areas due to mines and unexploded ordnance; and unburied remains of deceased humans and animals.

The impact of aerial vehicles, such as planes, helicopters, rockets, and drones, carrying ammunition, explosives, and fuel, has caused significant damage to forest ecosystems. The blast wave, shrapnel, and other fragments have broken tree trunks, branches, and roots, resulting in mechanical damage to plants and triggering forest fires. Powerful explosions have formed craters, leading to tree falls, damage to root systems, and disruption of the soil layer. A similar rocket explosion occurred in February 2024 in a forested area near the village of Buda-Babynetska, Kyiv Region. Figure 1 shows the crater formed by the rocket explosion.

Figure 1. Crater formed by a rocket impact southeast of the village of Buda-Babynetska, Kyiv Region, in 2024

Source: Examination of a rocket crater in the Kyiv region (2024)

Employees of the human rights organisation “Environment. People. Law” recorded the presence of a water-filled crater, and upon inspection of the area, the destruction of forest cover within a radius of approximately 25 meters was discovered. The formation of a water-filled crater indicated the destruction of the soil cover, which led to changes in the hydrological regime of the area and complicated the natural restoration of the ecosystem. The destruction of mixed forest cover near the village of Buda-Babynetska within a

25-metre radius indicated the loss of tree species (Scots pine (*Pinus sylvestris*), pedunculate oak (*Quercus robur*), silver birch (*Betula pendula*)) and shrub vegetation (common hazel (*Corylus avellana*), alder buckthorn (*Frangula alnus*), elder (*Sambucus nigra*)), which negatively impacted biodiversity, microclimate, and ecosystem functions, particularly air quality due to reduced photosynthetic activity. Additionally, soil and water contamination occurred due to explosive residues and heavy metals, causing long-term consequences for vegetation and fauna. The introduction of chemical substances into the soil altered the hydrological state of the area. Furthermore, explosions generated toxic inorganic and organic compounds, such as carbon monoxide, nitrogen dioxide, nitrogen oxides, and formaldehyde, which negatively affected the environment (Resolution of the..., 2021).

Mechanical damage was inflicted on trees and shrubs by ammunition fragments and small arms fire. Weakened plants were more susceptible to diseases and pests, as their immune and defence mechanisms were compromised. Moreover, non-viable plants were more prone to ignition, as their tissues were dry and easily combustible. Broken plant fragments served as ground fuel and leaf litter, increasing the risk of forest fire spread.

Forest fauna has been negatively impacted by various factors, including ecosystem changes, pollution, disruption of natural conditions due to human activity, forest fires, invasive species, and climate change. One consequence of these changes has been the transformation of vegetation cover, which is particularly noticeable in wartime conditions. In partially damaged or completely destroyed areas, synanthropisation processes have intensified, leading to the active spread of ruderal species. L. Zavialova *et al*. (2022) analysed the role of ruderal plants in the restoration of vegetation cover in transformed areas. Their research showed that the process of vegetation regrowth in cleared forest areas with destroyed upper tree canopy occurred relatively quickly. However, the regrowth in craters formed by artillery shell explosions was extremely slow, with almost no vegetation observed in the first year after the impact of military actions. Researchers noted the appearance of only a few common ragweed (*Ambrosia artemisiifolia* L.) and black locust (*Robinia pseudoacacia* L.) plants in one crater at the site of burned military equipment (Fig. 2), while no plants appeared in another crater (Fig. 3).

Figure 2. A crater area after shelling in 2022 with damaged military equipment, overgrown with *Ambrosia artemisiifolia* L. and *Robinia pseudoacacia* L.

Source: L. Zavialova *et al*. (2022)

Due to its high resistance to adverse environmental conditions, particularly drought, common ragweed is capable of rapidly colonising damaged or burned lands. Additionally, this species has a high capacity for seed reproduction, allowing it to quickly occupy new territories and dominate them. The black locust actively spreads after ecosystem disturbances, thanks to its ability to grow rapidly and adapt to various conditions, including those created after the burning of military equipment. The consequences of ragweed and black locust proliferation in these areas are significant. Ragweed, in particular, has a substantial impact on local flora, displacing native species and reducing biodiversity. Its aggressive reproduction disrupts natural food chains, as it is not always a primary food source for local animal species. Furthermore, ragweed is a potent allergen, significantly increasing the allergenic burden on the population, and causing seasonal allergies and other illnesses in people sensitive to its pollen. This leads to negative socio-economic consequences, including an increase in illnesses among the population, a decrease in labour productivity, and an increase in healthcare costs. Figure 2 depicts a post-shelling crater overgrown with adventive plants *Ambrosia artemisiifolia* L. and *Robinia pseudoacacia* L., also showing a localised area with partially destroyed military equipment. In 2022, in the Hetmanskyi National Natural Park, within the Neskuchanske forestry in the Sumy Region, where combat actions occurred, craters 0.5 and 1 meter deep showed no signs of herbaceous cover or regrowth of annual plants. This is attributed to the high degree of damage to the soil and vegetation cover due to the thermal impact of the explosion and the absence of a seed bank of adventive plant species in the soil. Figure 3 presents a photograph of a crater area after shelling, with a completely destroyed herbaceous cover due to a fire that occurred in 2022.

Figure 3 demonstrates a crater area after shelling in 2022, where the herbaceous cover was completely destroyed by fire, indicating the severe ecological consequences of combat actions, particularly soil cover degradation and vegetation loss. The presence of damaged areas poses a threat of outbreaks of alien species such as curlycup gumweed (*Grindelia squarrosa*), common ragweed (*Ambrosia artemisiifolia* L.), spiny burr grass (*Cenchrus longispinus* (Hack.) Fernald), oleaster (*Elaeagnus angustifolia* L.), and black locust (*Robinia pseudoacacia* L.), and has caused changes in soil structure, reduced soil fertility, and slowed down natural ecosystem recovery processes. Also, the fire resulted in the displacement of local plant species such as timothy-grass (*Phleum pratense* L.), red fescue (*Festuca rubra* L.), red clover (*Trifolium pratense* L.), and common bentgrass (*Agrostis tenuis* Sibth.). The loss of these plants has led to a decrease in biodiversity and disruption of vegetation cover structure, complicating the self-restoration processes of meadow ecosystems. Moreover, the physicochemical properties of the affected soil areas have significantly changed, including increased acidity and decreased humus content, which negatively impact further vegetation succession. In such conditions, the advantage was with adventive species resistant to stress factors, which could alter the ecological balance and cause secondary degradation of biogeocoenoses. Table 2 presents data on the spread of ruderal and adventive species in damaged forest areas and the reduction of forest cover.

Figure 3. A crater area after shelling in 2022 with completely destroyed herbaceous cover due to fire

Source: L. Zavialova *et al*. (2022)

Table 2. Spread of ruderal and adventive species in damaged forest areas and reduction of forest cover

Forest area	Percentage of forest stand damage, %	Herbaceous layer cover, %)	Common ragweed (*Ambrosia artemisiifolia*), %	Black locust (*Robinia pseudoacacia*), %	Reduction of forest cover, %	Comment on tree species
Crater near Buda-Babynetska Village	70	20	15	3	25	Destroyed young pine and oak
Hetmanskyi National Natural Park, Crater No. 2	90	10	8	0	30	Death of *Quercus robur*
Hoholivski Hai tract	50	35	5	4	15	Damaged *Pinus sylvestris*

Source: created by the authors

Table 2 shows that a significant spread of ruderal (*Ambrosia artemisiifolia*) and adventive (*Robinia pseudoacacia*) species was observed in damaged forest areas, which correlated with the degree of forest stand damage and the reduction in forest cover. The greatest losses of forest cover were observed in the Hetmanskyi National Natural Park (30%), where forest stand damage reached 90% and the death of pedunculate oak (*Quercus robur)* was noted. In the crater near the village of Buda-Babynetska, forest cover decreased by 25% due to the destruction of young pine and oak trees, with 70% forest stand damage. In the Hoholivski Hai tract, with 50% forest stand damage, forest cover decreased by only 15%, indicating a comparatively higher resilience of this community.

The lowest herbaceous cover (10%) was observed in the Hetmanskyi National Natural Park, which may indicate high soil degradation or slow vegetation recovery. The highest herbaceous cover (35%) was recorded in the Hoholivski Hai tract, which could be a result of active vegetation regrowth in damaged areas. The highest level of common ragweed (15%) was found in the crater near the village of Buda-Babynetska, indicating the aggressive spread of this allergenic species in degraded areas. Black locust (4%) was more prevalent in the Hoholivski Hai tract, which may indicate active succession towards false acacia. The territory of the Zalissia National Natural Park (Hoholivski Hai tract), located in the forest area of the Brovary District of the Kyiv Region and the Chernihiv District of the Chernihiv Region, showed ruderalisation of the herbaceous layer (Fig. 4).

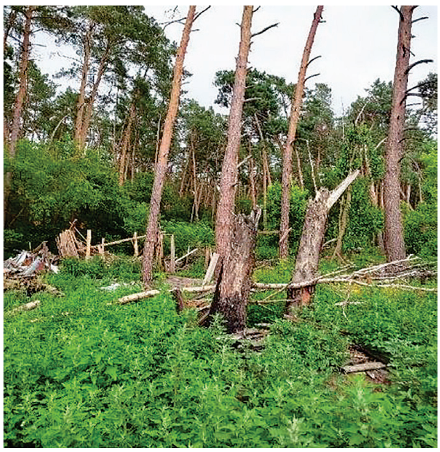

Figure 4. Damage to Scots pine trees (*Pinus sylvestris* L.) as a result of shelling in 2022
Source: L. Zavialova *et al*. (2022)

In the upper tier of coniferous forests, the presence of weed species from the *Chenopodium* L. s.l. a genus of the *Amaranthaceae* family led to a change in the composition and structure of the forest biocenosis, a reduction in biodiversity, and competition for resources between native and invasive species, indicating significant anthropogenic pressure or natural changes. Damage to the upper tree canopy and soil cover due to military actions created conditions for the introduction and establishment of adventive alien plant species. In 2014, during research in the Trokhizbenskyi Steppe branch of the Luhansk Nature Reserve of the National Academy of Sciences of Ukraine, which was affected by combat actions and the movement of military equipment from the Rostov Region of Russia (Fedenko, 2023), the appearance of a new species of adventive plant, *Sporobolus cryptandrus* (Torr.) A. Gray, a perennial bunchgrass, was recorded for the first time (Fig. 5).

Figure 5. The emergence of the adventive plant sand dropseed (*Sporobolus cryptandrus* (Torr.) A. Gray) on sands in the Trokhizbenskyi Steppe branch of the Luhansk Nature Reserve in 2014
Source: G.V. Gouz & V.V. Timoshenkova (2017)

The invasive species *Sporobolus cryptandrus* (Torr.) A. Gray, found on sparsely vegetated sandy areas, has led to the displacement of local species such as feather grass (*Stipa* spp.), narrow-leaved bluegrass (*Poa angustifolia*), spring sedge (*Carex praecox*), fringed pink (*Dianthus pseudosquarrosus*), and spurge (*Euphorbia* spp.). Shelling of forests has resulted in the death and injury of animals, forcing them to migrate and move into open areas in search of safety. Additionally, loud noises and stressful conditions have negatively affected the reproductive capacity of domestic and wild animals, reducing their populations. Research by D.A. Buyval & A.M. Pasternak (2024) has shown that elevated levels of the metabolite Bhydroxybutyrate in the milk of cattle indicate reproductive impairment, leading to a decrease in overall herd productivity and a reduction in the animals' ability to reproduce. Military actions have significantly impacted trophic chains in forest biocenoses through the destruction or substantial reduction of populations of certain species, leading to a disruption of the ecological balance. The death of predatory animals (wolves, foxes, lynxes, and birds of prey) has resulted in uncontrolled growth of their prey populations (small mammals such as hares, voles, various rodent species, and birds), while the reduction in herbivore populations, including deer, elk, roe deer, and wild boar, has affected vegetation regeneration. Research on the ecological consequences of military actions on the environment has revealed that in the long term, such changes can lead to a depletion of biodiversity, alteration of ecosystem structure, and even its degradation. Furthermore, soil damage, contamination with toxic substances, and disruption of natural self-purification mechanisms complicate ecosystem recovery for decades.

The occurrence and spread of fires in natural ecosystems were influenced by favourable weather conditions, forest site types, and species composition, all of which increased the risk of natural fire hazards. During wartime, the causes of fires included the use of incendiary munitions, the deliberate burning of dry herbaceous cover and forest vegetation for tactical purposes – to create barriers, obstacles or to alter the direction of forest fires – and to control fire spread or reduce fire hazards. Significant damage was inflicted on biocenoses following forest fires. The destruction of plants, animals, and microorganisms led to ecosystem collapse and biodiversity loss. Combustion products, including smoke and toxic substances, were released into the atmosphere and spread over long distances, polluting the air and causing global environmental problems.

During combat actions, when firefighting was not conducted, fires spread over large areas. Z. Cheng *et al*. (2023) noted that after forest fires, insect pests (pine mistletoe (*Viscum*, family *Viscaceae*), bark beetles (*Scolytinae Latreille*, family *Curculionidae*), tortrix moths (*Tortricidae* or *Olethreutidae*, family *Lymantriidae*), termites (*Isoptera*, family *Termitidae*)) proliferated, and fungal diseases spread, including ringless honey mushroom (*Armillaria tabescens*, genus *Armillaria*) and root rot (*Heterobasidion annosum*, genus *Heterobasidion*), wood-decay fungi (genera *Phellinus* and *Trametes*), white rot (genera *Ganoderma* and Fomes), and arbuscular mycorrhizal fungi of the genera *Glomus*, *Ambispora*, *Paraglomus*, and *Acaulospora*. Tree diseases such as pine rust, fusarium wilt, and pine pitch canker also spread, leading to vegetation damage and deterioration of forest ecosystem conditions. As forests lost important functions such as soil protection, water resource regulation, sanitary-hygienic, and ecological roles, landscape degradation, soil erosion, and water resource quality deterioration occurred. As a preventive measure against pine rust, fusarium wilt, and pine pitch canker, as well as pests, the treatment of seedlings and young pine trees with the bioorganic composition Mehanit Nirbator is recommended. This composition is based on biochemical fractions of basidiomycetes and is recommended for use by the Department of Physiology, Plant Biochemistry and Bioenergetics of the National University of Life and Environmental Sciences of Ukraine.

The research findings of O. Golan *et al*. (2022) demonstrated that the use of trap trees and treatment with the natural insecticide bifenthrin reduced the number of dead trees in stands, indicating the effectiveness of such measures in preventing the spread of bark beetles. K. Youssef (2023) found in his research that latent infections of Scots pine tree roots in areas with a low risk of root rot disease (*Heterobasidion annosum* s. l.) were quite common. Moreover, these infections were more frequent in areas with a higher site index, suggesting a greater likelihood of tree infection in more fertile soils. N. Erbilgin *et al*. (2021) reported that pines subjected to bark beetle attacks and drought exhibited a significant decrease in carbohydrate reserves, which limited their ability to synthesise protective diterpenes and increased the likelihood of tree death due to physiological depletion and mechanical damage to vascular tissue by beetles. In a study by C.J. Fettig *et al*. (2020), it was found that low doses of the chemical agent verbenone SPLAT® Verb (7 grams per tree) were effectively used to protect pine trees from a type of bark beetle, the mountain pine beetle (*Dendroctonus ponderosae* Hopkins), providing long-term protection of trees from pests. J. Kuang *et al*. (2024) found that the use of multi-temporal satellite data significantly improved the accuracy of monitoring forest stands affected by pine wilt disease compared to using single-time satellite images. Forests in active combat zones, affected by fires, cover 19.5% of Ukraine's territory (Fig. 6). This area spans a width of about 20 km on both sides of the front line.

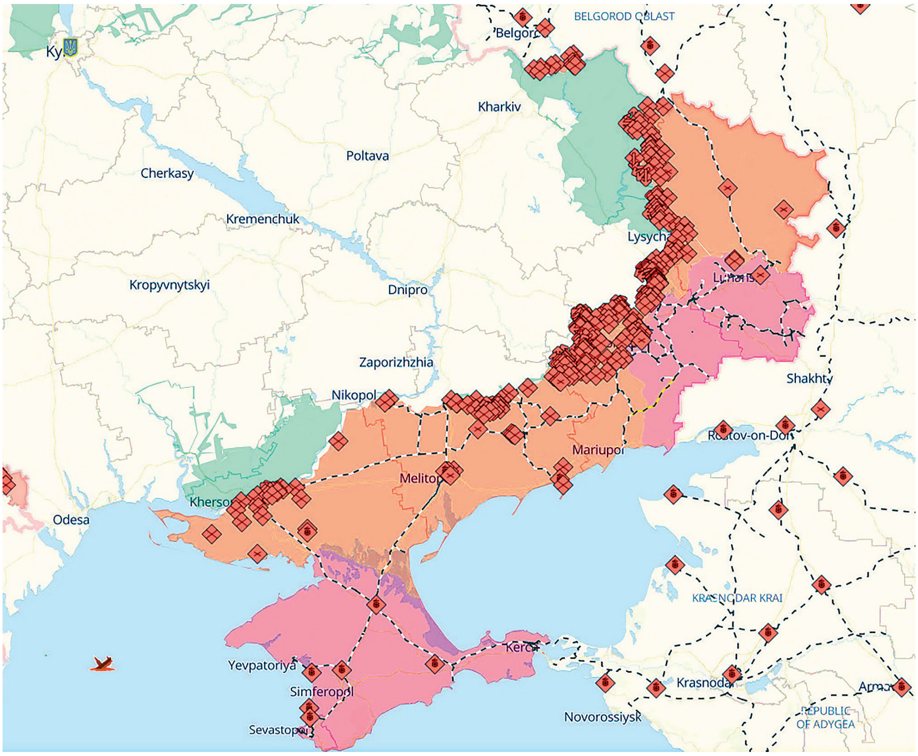

Figure 6. Map of combat actions in Ukraine as of 2nd March 2025

Source: DeepState (n.d.)

The map illustrates the situation on the front line in Ukraine as of 2nd March 2025. It includes data on active combat zones (dark red or brown), temporarily occupied territories (red), and territories liberated between late March 2023 and early April 2024 (blue). Combat actions in the conflict zone have negatively impacted forests, increasing the risk of large-scale fires.

Forest fires have been a significant source of environmental pollution and greenhouse gas emissions. As of early 2024, more than 8,000 hectares of forest land in temporarily occupied territories and combat zones were affected by forest fires, resulting in CO_2 emissions of 2,300 tonnes (based on estimates that 49,600 hectares were burned in 214 days of full-scale war, resulting in 14,336,000 tonnes of CO_2 emissions) (Occupants announce area..., 2024). The destruction of forests has also affected the local climate, causing changes in precipitation patterns and increasing the risk of droughts, which negatively impact agricultural production and, in turn, affect the country's food security. However, these impacts are not limited to the local level. Large-scale forest fires in Ukraine also contribute to global climate change, as CO_2 emissions from burned forests increase the overall concentration of greenhouse gases in the atmosphere.

Research indicates that significant losses of forest cover can lead to a reduction in precipitation due to the disruption of local and regional water cycle mechanisms. Forests play a crucial role in moisture evaporation and cloud formation, and their degradation can cause changes in atmospheric circulation, reduced air humidity, and prolonged periods of drought in the European region. Furthermore, the reduction in forest area has decreased their ability to absorb CO_2, which has amplified the greenhouse effect and contributed to overall warming. Forest ecosystem restoration is a critical task for mitigating climate change and preserving ecological balance. In addition to directly reducing CO_2 emissions, reforestation will contribute to the restoration of local water balance and reduce the risk of extreme weather events, such as droughts and abnormal temperatures.

The movement of military equipment has resulted in the breaking of trees and shrubs, the destruction of herbaceous cover, damage to plant roots, and soil compaction, which has hindered natural regeneration. Trees were felled and used to create shelters, dugouts, and camouflage structures to conceal military equipment, reducing its visibility from the air and the likelihood of detection by the enemy. It is important to note a trend towards a 5% decrease in carbon content at an average soil temperature of 15°C after forest clearing and the digging of equipment emplacements, leading to the destruction of the soil's humus horizon and a reduction in its fertility in 2024.

The construction of dugouts, defensive fighting positions, and trenches have disrupted the fertile soil layer by mixing it with deeper, less fertile horizons, reducing its biological activity. Furthermore, soil compaction and erosion processes have led to ecosystem degradation. Military activities have altered the terrain in forest environments, creating new depressions (defensive fighting positions, trenches, and craters) and destroying hills and irregularities, which has changed the hydrological regime of the area, promoting waterlogging or, conversely, increasing the risk of erosion. The main measures for restoring damaged ecosystems after the cessation of hostilities include soil remediation, tree and herbaceous cover planting, restoration of the water regime, and gradual natural ecosystem recovery. The ecological consequences of destroying plant root systems in forest ecosystems include the destruction of soil structure, reduced soil erosion resistance, and decreased moisture retention, leading to land degradation and biodiversity loss. Alternative methods for camouflaging military equipment that would cause less environmental damage include the use of camouflage nets, natural terrain irregularities, artificial shelters made from environmentally safe materials, and digital technologies to reduce visibility in infrared and radar ranges.

Forest ecosystems play a key role in ensuring the ecological security of the state, as their primary function is to regulate water balance, maintain soil fertility, and preserve biodiversity. In addition to their ecological significance, forests are also a source of resources for forestry, hunting, and agriculture. Uncontrolled logging, driven by military needs and the use of wood as fuel, has had negative consequences for forest ecosystems, leading to reduced forest cover, habitat destruction, decreased forest capacity to absorb carbon dioxide (CO_2), hydrological imbalance, desertification, and the transformation of forests into areas unsuitable for regeneration, biodiversity loss, and soil degradation and fertility reduction. Moreover, these negative impacts have led to changes in microclimate, increased erosion risk, and reduced access to natural resources, contributing to food crises in affected regions, particularly in the eastern and southern regions of Ukraine. It is important to note that the destruction of the Kakhovka Hydroelectric Power Plant has led to the destruction of the irrigation system in southern regions, negatively impacting agriculture and food security.

According to the Accounting Chamber of Ukraine, during the full-scale Russian invasion of Ukraine (as of the end of 2022; more current data as of 2025 is unavailable due to martial law), 3 million hectares of forest were damaged and permanently destroyed (Panchenko *et al*., 2023). The restoration of damaged and burned forests will take 20-30 years. According to information provided by the Operational Headquarters for Recording Environmental Crimes, the regions most affected by mining and forest fires due to enemy shelling and deliberate arson were: Chernihiv Region, where nearly 400,000 hectares of forest were damaged; Sumy Region, where approximately 290,000 hectares of forest plantations were destroyed; Luhansk Region, where approximately 200,000 hectares of forest were lost; and Kyiv, Zhytomyr, and Kharkiv regions, where 120,000 to 160,000 hectares of forest land were damaged in each region.

Military actions have significantly impacted the biodiversity of the terrestrial plant layer through mechanical damage to vegetation during the movement of equipment, construction of fortifications, and explosions. This has led to the destruction of natural habitats, a reduction in species numbers, and even the complete elimination of rare flora. Plants that grow only in specific ecological conditions have been particularly affected. These include endemic species (such as those from the *Caryophyllaceae* or *Orchidaceae* families), relict species (such as yew (*Taxus baccata*), ginkgo (*Ginkgo biloba*), sundew (*Drosera*), dwarf palmetto (*Sabal minor*), and white waterlily (*Nymphaea alba*)), as well as red-listed plants (such as edelweiss (*Leontopodium alpinum*) or pheasant's eye (*Adonis vernalis*)), which have a limited distribution range.

Unburied bodies of deceased soldiers and animals have become a source of disease transmission, including infectious diseases (such as tularemia, leptospirosis, anthrax, and rabies), which are transmitted through contact with the body or from insects that infest the corpses. Zoonoses, such as rabies and salmonellosis, are spread through contact with dead animals. Insects such as flies, ticks, and fleas, which act as vectors for infection, have also proliferated. The improper burial of bodies in forests leads to groundwater contamination, including the leaching of toxic substances like ammonia from the bodies into the soil and groundwater, the contamination of aquifers with pathogens that can cause diseases in humans and animals, and the release of various biological agents and organic residues, resulting in ecosystem imbalance and environmental resource contamination.

Territories contaminated with unexploded mines and ordnance due to military actions can be categorised into several types: areas with active mines or unexploded ordnance posing an immediate threat to humans and animals; forest massifs where reforestation is impossible due to the danger of active mines and ordnance; and areas requiring specialised treatment and clearance before they can be used for forestry or other activities. The destruction of forest ecosystems has significantly impacted the economies of regions where forestry is the primary sector. Mass forest losses have reduced timber harvesting volumes, led to job losses, and deprived local populations of income. Furthermore, the mining of forest areas due to combat actions has made their use for economic purposes impossible in the long term, posing a threat to human life, limiting regional economic development opportunities, and requiring significant financial resources for demining and restoration. Consequently, poverty levels have risen among the population, particularly in rural areas where forests are a source of income. The loss of natural resources has forced people to migrate, contributing to demographic changes and weakening local communities.

Postconflict forest restoration is a complex process that requires a comprehensive approach, including natural regeneration mechanisms and targeted ecosystem restoration measures. One of the key natural mechanisms is the symbiosis of mycorrhizal fungi with plant root systems, which improves nutrient access, enhances resistance to drought and pathogens, and accelerates forest soil recovery. Soil microorganisms play an important role in this process, ensuring organic matter decomposition, nitrogen enrichment, and the creation of favourable conditions for tree seed germination. Additionally, forests can self-regenerate through seed regeneration and vegetative reproduction, which depends on the ability of certain tree species to form root offspring and adapt to altered environmental conditions. To accelerate natural recovery, a set of measures aimed at stabilising the ecosystem and restoring forest cover must be implemented. First and foremost, the condition of soils and ecosystems must be assessed through laboratory analysis of heavy metal, explosive residue, and toxic element contamination, as well as an evaluation of soil erosion and moisture levels. One effective measure is the introduction of mycorrhizal fungi, which helps improve soil biota and stimulate tree growth. Additionally, the use of seedlings with a closed root system is advisable, as it increases their survival rate and ensures rapid restoration of forest areas. To stabilise the soil and prevent erosion processes, hydroseeding, which involves sowing herbaceous plants and shrubs with added fertilisers and mulch, can be used. Phytoremediation, the planting of plants capable of accumulating and neutralising heavy metals, such as poplar, willow, and sunflower, is a crucial component of the recovery process. Furthermore, the use of green manure crops, particularly lupine and clover, helps improve soil structure and facilitate its recovery. Monitoring the condition of forest ecosystems should be carried out through the observation of flora and fauna, remote sensing, and the use of bioindicators, such as lichens and mosses, to assess atmospheric pollution levels. Therefore, effective post-conflict forest restoration requires the integration of natural regeneration mechanisms with modern technologies, including mycorrhisation, planting of trees with a closed root system, hydroseeding, and the application of biological preparations, which will promote rapid ecosystem recovery, enhance their ecological resilience, and ensure biodiversity conservation.

The National Council for the Recovery of Ukraine from the War has developed a draft of the Recovery Plan of Ukraine (draft) (2022), which includes materials from the Working Group "Environmental Security". In total, the Recovery Plan of Ukraine includes 76 environmental projects with a total budget of EUR 25.5 billion. The Recovery Plan of Ukraine in the field of environmental safety envisages the implementation of measures in three stages: the first stage (2022) has already been completed. It involved the development of a methodology for determining damage and losses caused by the destruction or damage of Ukraine's forest fund, forest plant species, and damage to bioresources. The second stage (2023-2025) is to include the development of an Action Plan for the implementation of the State Strategy of Forest Management in Ukraine up to 2035, the implementation of projects for the restoration and modernisation of environmental infrastructure, and the introduction of modern technologies to reduce pollution and improve environmental quality. The third stage (2026-2032) aims to achieve sustainable development, integrate environmental standards into all sectors of the economy, and ensure environmental safety at the national level. The presence of craters formed by explosions, as well as the destruction of vegetation cover, has led to the disruption of the hydrological regime, particularly changes in the water balance of forest areas. The restoration of Ukraine's forest ecosystems after the hostilities is necessary, including the implementation of measures such as soil decontamination from toxic substances, vegetation cover restoration, and water resource monitoring.

Discussion

Analysing the obtained research results, it can be concluded that the increased intensity of wildfires due to military actions has negatively impacted natural ecosystems. In particular, one of the most critical problems was the disruption of vegetation recovery, which led to biodiversity loss and changes in the structure and functioning of forest phytocoenoses, with long-term consequences for the stability and resilience of these ecosystems.

It was established that the increased intensity of wildfires and deforestation in temporarily occupied territories and combat zones in 2024 had severe negative consequences for the ecosystem, particularly for forest soils, due to a decrease in soil organic carbon content. A similar issue was raised by F. Niccoli *et al*. (2023). The authors found that fires significantly reduced the ability of trees to photosynthesise and absorb carbon dioxide (CO_2) due to defoliation and crown damage. The results of the current study did not align with the conclusions of F. Niccoli *et al*., as the current study investigated the impact of soil organic carbon on forest ecosystems rather than the physiological state of trees, as in the research by the analysed authors. In the case of the conducted research, the impact of soil organic carbon may be a longer-term process, with its consequences becoming apparent over a more extended period. In the short term, even if trees have sustained significant damage, the soil may continue to change due to the burning of organic matter and the disruption of soil structures. The research by F. Niccoli *et al*. was conducted in central Italy, while the present study was carried out in Ukraine, leading to differences in conclusions. Geographical factors, such as climate, soil types, flora, and fauna, can influence the recovery of forest ecosystems after fires. The current study employed methods assessing soil organic carbon content, focusing on the chemical and physical characteristics of the soil, whereas F. Niccoli *et al*. research concerned tree physiology. The response to fires may vary depending on the type of forest ecosystem (e.g., coniferous or deciduous forests). It is important to consider that soil organic carbon in deciduous forests generally has different properties than in coniferous forests. Fires can have varying impacts on different tree types and, consequently, on soil organic carbon.

The reduction in soil organic carbon content in forest ecosystems in temporarily occupied territories and combat zones in 2024 is directly related to the impact of deforestation and the digging of emplacements for military equipment, which affected the topsoil layer (Matkivskyi & Taras, 2024). J. Adkins & J.R. Miesel (2021) have also studied this topic. Their research showed that at high soil temperatures (up to 200°C), the soil's ability to absorb carbon decreased. Similar conclusions were reached in the presented study, as the results indicate a trend towards a decrease in carbon content at an average soil temperature of 15°C after deforestation, leading to the destruction of the soil's humus horizon and a reduction in its fertility.

According to the conclusions of the current study, soil organic carbon content decreased by 5% in 2024, which is associated with soil degradation following deforestation. E. Grieco *et al*. (2024) also studied this problem. They found that the conversion of primary forests to other land cover types significantly affected total carbon stocks, particularly aboveground biomass carbon and soil organic carbon. A 5% reduction in soil organic carbon content after deforestation is a significant indicator, as organic carbon is a crucial component of soil ecosystems and plays a key role in maintaining soil fertility and climate stability (Lozinska *et al*., 2024). In pristine forest ecosystems, soil organic carbon content can vary, but it is generally significantly higher compared to anthropogenically altered areas (Kruglov *et al*., 2023). For example, soil organic carbon content in natural forests can range from 20 to 80 t/ha, depending on the forest type, climatic conditions, and soil type. This correlates with data obtained by E. Grieco *et al*., who found that the conversion of primary forests to other land cover types, such as agricultural or industrial land, reduces soil organic carbon due to a decrease in aboveground biomass. A 5% reduction in carbon content can have serious long-term consequences (Romanchuck *et al*., 2017). If this process continues, it can lead to soil degradation, reduced soil capacity to retain moisture and nutrients, as well as decreased biodiversity and increased greenhouse gas emissions. Furthermore, long-term carbon loss can impair the ability of ecosystems to recover from anthropogenic changes. Thus, comparing the results of this study with the research of E. Grieco *et al*. confirmed that changes in soil organic carbon after deforestation are critical for ecosystem stability and require urgent measures for the preservation and restoration of forest ecosystems.

It was noted that in January 2024, more than 8,000 hectares of forest land were affected by forest fires in temporarily occupied territories and active combat zones, resulting in CO_2 emissions of 2,300 tonnes and the accumulation of greenhouse gases in the atmosphere. A. Brito *et al*. (2022) studied a similar problem. The scientists found that increased greenhouse gas emissions and deforestation had severe consequences for the local ecosystem, including a reduction in biodiversity, forest degradation, and disruption of the water balance, as well as a decrease in groundwater levels, which negatively affected agricultural production. This assertion can be agreed with, as the degradation of forest ecosystems indeed reduces the ability of forests to absorb carbon dioxide, further increasing the concentration of greenhouse gases.

High concentrations of zinc, manganese, copper, lead, and other metals in soil after the 2022-2024 forest fires posed a danger to the environment (Biyashev *et al*., 2024). G. Singh *et al*. (2021) raised a similar issue. The authors obtained results showing that the metal pollution index ranged between 1.84 and 6.62, and plants growing in areas S10 to S17 accumulated particularly high concentrations of metals. The assertion of G. Singh *et al*. can be agreed with, as the process of phytoextraction can negatively affect plant growth, reduce their viability, and even cause death.

It was established that soil compaction in 2022-2024 due to the movement of heavy military equipment and vehicles caused damage to its structure and degradation of the soil environment. M.R. Shaheb *et al*. (2021) have studied a similar issue. The researchers obtained results showing that soil compaction increased its bulk density and strength, decreased porosity and hydraulic properties, and slowed the root growth of forest plant species. The assertion of

M.R. Shaheb *et al*. can be agreed with, as delayed root growth indeed reduces the efficiency of nutrient and water absorption by plants.

It was found that after fires caused by military actions in 2014, a new species of adventive plant, sand dropseed (*Sporobolus cryptandrus* (Torr.) A. Gray), appeared in the Trokhizbenskyi Steppe branch of the Luhansk Nature Reserve, displacing local species such as feather grass (*Stipa* spp.), narrow-leaved bluegrass (*Poa angustifolia*), spring sedge (*Carex praecox*), fringed pink (*Dianthus pseudosquarrosus*), and spurge (*Euphorbia* spp.). A.K. Verma *et al*. (2024) have studied a similar issue. In their research, the authors found that invasive plant species not only increased the frequency and intensity of forest fires but also changed the structure of local ecosystems, suppressed the growth of native species, and created conditions conducive to the further spread of invasive plants. This assertion should be agreed with, as invasive species are indeed capable of accumulating large amounts of dry biomass, which becomes highly flammable material.

It was demonstrated that the upper parts of plants, particularly trees, shrubs, and grasses, were most vulnerable to fires. A similar study was conducted by A. Ishak (2024). The researcher's results showed that during periods of low humidity and high temperatures, the protected and tourist zones of the national park were particularly vulnerable to forest fires. This assertion can be agreed with, as low humidity reduces the water content in plants and soil, making them more susceptible to ignition, and high temperatures promote faster drying of vegetation and increase the likelihood of outbreaks.

For the effective protection of Scots pine trees against pathogens of pine rust, fusarium wilt, and pine pitch canker, as well as against pests such as pine mistletoe (*Viscum*, family *Viscaceae*), bark beetles (*Scolytinae Latreille*, family *Curculionidae*), tortrix moths (*Tortricidae* or *Olethreutidae*, family *Lymantriidae*), and other insect pests, the use of the innovative preparation Mehanit Nirbator is recommended. This preparation is based on biochemical fractions of basidiomycetes and is designed for the restoration of forest resources after fires. K. Zhang & J. Stenlid (2023) studied a similar issue. Their research revealed that protocols for monitoring and managing Scots pine blister rust epidemics, designed to detect the rust fungus (*Cronartium pini*), were effective and specific for identifying this fungus in Scots pine samples. Using these protocols, they were able not only to detect the presence of this pathogen in asymptomatic and symptomatic trees but also to track the emergence of Scots pine blister rust in Northern Europe. The conclusion of K. Zhang & J. Stenlid is agreeable, as the application of these developed protocols allows for the timely detection and control of the spread of Scots pine blister rust, contributing to the effective management of the phytosanitary condition of forest stands and reducing economic and ecological losses.

It was observed that at the crater site resulting from shelling in 2022 within the Hetmanskyi National Natural Park, specifically in the Neskuchanske forestry of the Sumy Region, there has been a proliferation of non-native plant species such as curlycup gumweed (*Grindelia squarrosa*), common ragweed (*Ambrosia artemisiifolia* L.), spiny burr grass (*Cenchrus longispinus* (Hack.) Fernald), oleaster (*Elaeagnus angustifolia* L.), and black locust (*Robinia pseudoacacia* L.). This has led to the displacement of native plant species, including timothy-grass (*Phleum pratense* L.), red fescue (*Festuca rubra* L.), red clover (*Trifolium pratense* L.), and common bentgrass (*Agrostis tenuis* Sibth.). A similar issue was studied by M. Harrison *et al*. (2024). Their research indicated that the burned forest not only experienced significant structural and microclimatic changes but also suffered substantial biodiversity loss, particularly in the species diversity of trees, molluscs, and butterflies. The conclusions of M. Harrison *et al*. are valid, as the loss of habitats, changes in resource availability, and other ecological factors following a fire can significantly alter an ecosystem.

This section has reviewed studies on the ecological consequences of forest fires and military-related activities on natural ecosystems. Particular attention was paid to the impact on forest soils, specifically the reduction of soil organic carbon, which is a crucial factor in maintaining soil health and ecosystem stability. In the context of the studied ecological impacts of forest fires and military activities on natural ecosystems, especially forest soils, it is necessary to consider possible strategies for the restoration of damaged forest areas. These include implementing measures to restore biodiversity through the planting of native trees and plant species that support natural ecosystem regeneration. Habitat restoration programs for native species, such as feather grass, sedge, and other grasses, will help prevent the displacement of local species by invasive plants. This can be achieved through methods to control invasive species, such as mechanical removal or limiting their spread using chemical or biological means.

Conclusions

During the 2024 study, the following tasks were carried out: as a result of the analysis of the impact of military actions on forest ecosystems, it was found that military activities caused serious ecological consequences, including the transformation of vegetation cover, a decline in biodiversity, and disruption of trophic chains. In identifying the main factors of forest damage, it was noted that the primary causes were fires resulting from military actions, leading to the death of a portion of the flora and fauna, as well as the spread of pests and diseases among woody plants. Recommendations for forest restoration were developed, and a set of measures was proposed for the rehabilitation of forest ecosystems, including strategies for combating invasive species, restoring soil cover, and preserving biodiversity.

Based on theoretical research using open-source information, it has been shown that in 2014, the emergence of a new species of adventive plant, sand dropseed, was first recorded in the Trokhizbenskyi Steppe branch of the Luhansk Nature Reserve of the National Academy of Sciences of Ukraine. This led to the displacement of native species such as feather grass, narrow-leaved bluegrass, spring sedge, fringed pink, and spurge. The impact of explosions and forest fires destroyed important tree and shrub species, including Scots pine, pedunculate oak, and silver birch, as well as shrubs like common hazel, alder buckthorn, and elder. Following the damage to territories and the formation of craters, there was a noticeable spread of invasive species, particularly ragweed and black locust. The loss of native plant species, such as timothy-grass, red fescue, red clover, and common bentgrass, disrupted the structure of the herbaceous cover, negatively affecting food chains in forest ecosystems. The replacement of natural species with ruderal and invasive plants altered ecosystem functions, such as carbon sequestration, soil stability, and water balance.

For the effective restoration of forest ecosystems following military actions, it is proposed to conduct a detailed analysis of soils to determine the level of contamination by heavy metals, toxic elements, and explosive residues. The introduction of mycorrhizal fungi into soils damaged during military activities is recommended, as it will contribute to faster ecosystem and forest biota recovery. For the rapid restoration of forest areas, it is advisable to use seedlings with a closed root system, which increases their survival rate in damaged soil conditions. Hydroseeding herbaceous plants and shrubs with added fertilisers and mulch can help restore soil cover more quickly, protecting it from erosion, improving soil structure, and increasing its fertility.

The limitation during the 2024 study of areas affected by forest fires was the unavailability of data on the precise level of soil contamination with heavy metals and explosive residues in some zones. This limited the ability to accurately assess the extent of contamination and its impact on ecosystem recovery processes. The study did not account for additional factors that may affect recovery, such as changes in climatic conditions, the level of anthropogenic pressure on forest ecosystems after military actions, and the potential impact of invasive species on biodiversity and ecosystem resilience. The prospect for further research includes conducting more detailed monitoring of ecological changes in regions damaged by military actions to develop more effective methods for restoring forest ecosystems.

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Conflict of Interest

None.

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Вплив бойових дій на лісові екосистеми: виклики для довкілля, національної безпеки та стійкості держави

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Анотація. Метою дослідження був аналіз впливу активних військових дій на біорізноманіття та лісові ресурси. У дослідженні використано такі методи: аналіз супутникових даних з відкритих джерел та повідомлень ЗМІ, а також методи узагальнення та систематизації. Встановлено, що накопичення сухої біомаси після пожеж сприяло поширенню лісових пожеж. Утворення кратероподібних западин внаслідок вибухів змінило склад лісових насаджень та водний баланс, що вплинуло на водопостачання регіону та призвело до перезволоження або висушування земель. Результати дослідження свідчать, що у 2024 році після обстрілу лісового масиву поблизу села Буда-Бабинецька Київської області було знищено лісовий покрив у радіусі 25 метрів. Серед них такі види рослин, як сосна звичайна (*Pinus sylvestris*), дуб черешчатий (*Quercus robur*) та береза срібляста (*Betula pendula*). Аналіз інформації з відкритих джерел та повідомлень у засобах масової інформації показав, що рудеральні види, такі як амброзія полинолиста (*Ambrosia artemisiifolia* L.) та лобода чорна (*Robinia pseudoacacia* L.), колонізували пошкоджені ділянки. Це свідчить про активне заселення рослинності видами, здатними до швидкого відновлення після порушень. У зонах вибухових кратерів процеси відновлення рослинного покриву відбувалися повільно.

Наприклад, в одному з кратерів Гетьманського національного природного парку в Сумській області було зафіксовано лише кілька екземплярів амброзії та чорної сарани, тоді як інший кратер залишився без будь-якої рослинності. Для сприяння відновленню лісів в Україні після припинення активних бойових дій було рекомендовано застосування мікоризних грибів, використання саджанців, вирощених у контейнерах, та гідропосіву. Отримані дані про стан лісових масивів можуть сприяти розробці стратегій збереження та відновлення пошкоджених пожежами лісових екосистем

Ключові слова: пожежі; воронки; інвазії; рудеральні види рослин; біорізноманіття; рослинний покрив

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Water resources as a factor of ecological sustainability in forest ecosystems of Kyrgyzstan and Kazakhstan: Challenges and prospects for cooperation

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Abstract. The relevance of the study is conditioned by the growing impact of climate change and anthropogenic stress on water resources, which are crucial for maintaining the ecological sustainability of forest ecosystems in Central Asia. The purpose of the study was to assess changes

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in the water resources of Kyrgyzstan and Kazakhstan during 2014-2024 and determine their impact on the ecological sustainability of forest ecosystems. The research methods included the analysis of hydrological data on the quantity and quality of water resources during the specified period, and the analysis of scientific sources on the relationship between water balance, biodiversity, and soil conditions. In particular, the water level in large rivers (Naryn, Ili), changes in water temperature, chemical pollution, and the dynamics of forest areas were analysed. The results showed that the water level in the Naryn River decreased by 8% due to melting glaciers and increased water intake, while in the Ili River this figure was 6% due to reduced inflows from China and increased water consumption. The average water temperature increased by 1.0-1.2°C, which reduced the concentration of dissolved oxygen and negatively affected biodiversity. Water pollution from industrial and agricultural discharges increased by 10-15%, exacerbating the degradation of coastal ecosystems and biodiversity. The data indicate the relative stability of the overall forest fund of Kyrgyzstan, but there is a decrease in the area of land covered with forest, which raises concerns about the effectiveness of conservation measures. Reforestation shows unstable dynamics due to climate change and water scarcity. The reduction in forest areas was 5% in Kyrgyzstan and 7% in Kazakhstan, with the largest losses observed in the Ili River basin. The decrease in biodiversity in Kazakhstan reached 12%, while in Kyrgyzstan, the decrease in forest area worsened the water stress in mountainous regions. The findings highlight the close relationship between the state of water resources and the ability of forest ecosystems to perform ecological functions

Keywords: climate change; biodiversity; biogeocoenosis; river basins; vegetation

Introduction

Water resources play a critical role in ensuring environmental sustainability, especially in forest ecosystems, which are important natural regulators of climate, water balance, and biodiversity. Kyrgyzstan and Kazakhstan, located in Central Asia, are countries with diverse landscapes, where forests perform a key function in maintaining ecosystem balance. However, these countries face numerous challenges in the field of water resources management, which makes it necessary to investigate this issue in depth.

The importance of water resources in forest ecosystems is conditioned by their ability to retain soil moisture, regulate runoff, and ensure the stability of local and regional climatic conditions. However, climate change, forest degradation and poor use of water resources threaten the sustainable functioning of these ecosystems (Mustafayeva & Tagiyev, 2023). In particular, in Central Asia, reduced snow reserves, water pollution, and increased anthropogenic impact put significant pressure on natural systems (Ongayev *et al.*, 2024). Moreover, the transnational nature of many water basins in the region requires international cooperation to effectively manage and conserve these resources.

Research in the field of water resources management in Central Asia covers a wide range of topics. In particular, A.M. Anghelescu & I.D. Onel (2024) analysed the role of the European Union in developing water management policies in the region, focusing on examples of the Aral Sea demonstrating the need for international cooperation to overcome the water crisis. Other researchers consider the reproduction of forest resources in the context of sustainable development. For example, K.T. Abayeva *et al.* (2024) emphasised the need to optimise forest management in Kazakhstan, in particular, through the integration of water-saving technologies. Research in the field of water resources management in Central Asia covers a wide range of topics. In particular, S. Missall *et al.* (2022) investigated the rational use of forests along water basins in Kyrgyzstan, emphasising their role in maintaining the water balance. B. Atantayeva *et al.* (2024) considered the problems of ecosystem conservation and security on the example of the territory of "Semey Ormani" in Kazakhstan, emphasising the need for integrated management of forest and water resources. X. Wang *et al.* (2020) focused on assessing water security and resource development in Central Asia, which is important for maintaining ecosystem stability in the region.

In turn, O. Abraliyev *et al.* (2024) investigated the optimisation of irrigated land use in Kazakhstan, pointing out the importance of a systematic approach to water resources management. The study by A. Ozenbayeva *et al.* (2022) considered the legal aspects of the regulation of transboundary water resources of the Republic of Kazakhstan, in particular, the existing international treaties, national legislation and mechanisms of water resources management in the context of regional cooperation were analysed. Thus, there are a significant number of studies that cover certain aspects of water resources in the region, but not enough attention is paid to their impact on the ecological sustainability of forest ecosystems and the prospects for cooperation between Kyrgyzstan and Kazakhstan.

Gaps in the coverage of water resources in Central Asian Forest ecosystems include insufficient analysis of the relationship between climate change, the state of water resources and environmental sustainability. In addition, the effectiveness of existing cooperation strategies between countries, in particular, in the field of forest and aquatic ecosystems conservation, is relevant. Thus, the study is focused on investigating the role of water resources in ensuring the ecological sustainability of forest ecosystems in Kyrgyzstan and Kazakhstan, considering current challenges and opportunities for cooperation. Its purpose was to analyse the relationship between the state of water resources and the stability of forest ecosystems, assess the impact of water scarcity on forest landscapes, and identify effective approaches to their conservation and management.

Materials and Methods

A comprehensive approach was used to conduct the study, including the collection, analysis, and synthesis of data from various sources. The main materials of the study included official statistics, environmental reports and information obtained from the state registers of water and forest resources of Kyrgyzstan and Kazakhstan. The data used covered the period from 2014 to 2024, which allowed tracking the dynamics of changes in the state of water resources and their impact on forest ecosystems. Data on the state of water resources in Kyrgyzstan were obtained from the Ministry of Natural Resources, Ecology and Technical Supervision of the Kyrgyz Republic (n.d.), which included information on the water level in key rivers and lakes of the country, and the National Statistical Committee of the Kyrgyz Republic (n.d.). For Kazakhstan, data from the Ministry of Ecology and Natural Resources of the Republic of Kazakhstan (n.d.) were used, which contained statistics on water consumption, the level of water pollution, and the hydrological state of rivers. In addition, information from the Bureau of National Statistics (n.d.) on the economic aspects of the use of water resources in forestry was attracted.

Materials from the state registers of the forest fund of both countries were used to assess the ecological sustainability of forest ecosystems. The data included indicators of biodiversity, the area of forest stands, and their ecological state. In particular, official reports of the State Register of the Forest Agency of the Kyrgyz Republic (n.d.) and similar structures in Kazakhstan were considered (Ministry of Ecology..., n.d.). Regional forest restoration programmes, such as the "Zhasyl El" programme in Kazakhstan, which aims to increase forest cover, were also taken into account. In addition, the study was based on an analysis of the scientific literature on the relationship between water resources and forest ecosystems in the context of environmental sustainability (Decree of the Government of the Republic of Kazakhstan No. 632 "On the..., 2005). In particular, papers that consider regional aspects of changes in the water balance and their impact on forest ecosystems, papers that analyse the mechanisms of adaptation of forest ecosystems to changes in the water regime, and studies on natural resource management based on environmental factors were analysed (Missall *et al.,* 2022; Wang *et al.,* 2022).

The study included several stages of working with data. At the first stage, the initial information necessary for creating a single database was systematised and processed. The main focus was on the development of structured data on quantitative indicators of water resources, forest cover area, biodiversity level, and economic aspects of the use of natural resources in Kazakhstan and Kyrgyzstan. Python and Microsoft Excel software tools were used to process large amounts of data. Python was used to automate data collection, processing, and pre-analysis processes, while Microsoft Excel provided additional verification of the received data and its visual structuring.

The second stage of the study included a qualitative analysis of scientific literature and statistical reports related to water resources management, the state of forest cover, and the impact of anthropogenic and climatic factors on environmental sustainability in the region. The main focus was on materials that highlight local features of the relationship between water resources and forest ecosystems. The collected data helped to identify key impact factors and assess their significance for ensuring ecosystem sustainability.

At the final stage, the results obtained were synthesised, which allowed formulating conclusions about the impact of water resources on forest ecosystems. The results of the analysis contributed to a better understanding of the main dependencies and helped to identify recommendations for water management to maintain environmental sustainability. The integrated approach provided a deep study of the problem and allowed to formulate conclusions that are relevant both for the scientific community and for practical use. Overall, the study was based on the integration of statistical and analytical data to gain a comprehensive understanding of the relationship between water resources and the ecological sustainability of forests in the region.

Results

General state of water resources of the regions under study. Analysis of data on water resources of Kyrgyzstan and Kazakhstan for the period 2014-2024 indicates significant changes in the level of water supply, water quality, and hydrological state of key reservoirs in the region (Table 1).

Table 1. General state of water resources of Kazakhstan and Kyrgyzstan for the period 2014-2023

Indicator	Unit of measurement	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Kazakhstan											
Renewable fresh water resources (annual runoff)	mln. m^3	108,100	115,600	160,000	122,100	110,700	107,600	87,300	76,800	82,700	103,900
Fresh water intake	mln. m^3	23,078	21,661	21,634	22,454	23,542	23,516	24,585	24,518	24,967	24,366
Fresh water intake per capita	m^3	1,334.9	1,234.8	1,215.8	1,244.8	1,288.1	1,270.2	1,310.8	1,290.4	1,271.5	1,224.4
Water resource exploitation index	%	21.35	18.74	13.52	18.39	21.27	21.86	28.16	31.92	30.19	23.45
Level of load on water resources	%	32.01	30.04	30.01	31.14	32.65	32.62	34.10	34.01	34.63	33.79
Kyrgyzstan											
Water intake from natural sources	mln. m^3	-	-	-	-	-	8,068.7	8,017.9	7,999.5	8,741.9	8,872.5
Water intake from underground horizons	mln. m^3	-	-	-	-	-	254.8	249.8	252.9	258.4	271.0
Water consumption	mln. m^3	-	-	-	-	-	5,211.1	5,237.5	5,310.0	5,844.0	6,028.0
For production needs	mln. m^3	-	-	-	-	-	84.3	82.5	80.2	79.1	67.6
For irrigation and agricultural water supply	mln. m^3	-	-	-	-	-	4,920.7	4,942.0	4,986.9	5,515.6	5,697.0
Wastewater volume	mln. m^3	-	-	-	-	-	99.3	123.4	133.1	132.2	132.2

Note: data for Kyrgyzstan are provided according to the information of the water resources service under the Ministry of Water Resources, Agriculture and Processing Industry of the Kyrgyz Republic for the period 2019-2023. Despite the fact that the analysis covers the period 2014-2024, data for 2024 are not included in the table, since at the time of the study they have not yet been published on official statistical resources
Source: compiled by the authors based on National Statistical Committee of the Kyrgyz Republic (n.d.), Ministry of Ecology and Natural Resources of the Republic of Kazakhstan (n.d.), Bureau of National Statistics (n.d.)

Table 1 shows the instability of the water balance in Kazakhstan, where the annual runoff varies from 87.3 to 160 mln. m^3, which indicates the impact of climate change. Although fresh water intake remains stable (21.6-24.9 mln. m^3), the load on water resources reaches a critical 34%, and a decrease in the per capita intake indicates an increase in demographic pressure. In Kyrgyzstan, there is a stable intake of water from natural sources (8,017.9-8,872.5 mln. m^3) and a gradual increase in water consumption, which in 2023 reached 6,028 mln. m^3, mainly for agriculture. Compared to Kazakhstan, Kyrgyzstan has a lower level of load on water resources, but its dependence on groundwater and irrigation increases. In Kazakhstan, the high level of resource exploitation and instability of the water balance require the introduction of effective water resources management.

In Kyrgyzstan, the average water level in the main rivers, in particular in the Naryn River, decreased by 8% compared to the initial period of the study. The main reason for this is the intense melting of glaciers caused by an increase in average annual temperatures, which leads to a decrease in the total ice cover and, accordingly, long-term water reserves in rivers. In addition, climate change is accompanied by an increase in the frequency of droughts and a shift in snowmelt regimes, which leads to additional stressful conditions for water resources. Anthropogenic impact, in particular, water intake for irrigation agriculture and hydropower, further exacerbates the situation (Ushkarenko *et al.*, 2024). An increase in the average summer water temperature by 1.2°C leads to a decrease in the concentration of dissolved oxygen, which negatively affects the chemical composition of water and the biodiversity of aquatic ecosystems. In addition, according to research, river water pollution caused by discharges from industrial and agricultural enterprises has increased by 15% over the past decade (Wang *et al.,* 2022).

In Kazakhstan, there is a similar trend of decreasing water resources, in particular in the Ili River basin During the analysed period, the water level in the basin decreased by 6%. The main factors are an increase in domestic water consumption, in particular in agriculture, where the area of irrigated land is actively expanding, and a reduction in the inflow of water from China, which is conditioned by the intensive use of water resources for the economic development of Xinjiang. Lower water levels in Lake Balkhash, which is heavily dependent on the Ili River, have led to degradation of coastal forest ecosystems, reduced biodiversity, and soil salinisation. An increase in the water temperature in the lake by 1.0°C, together with an increase in the level of pollution by 10%, leads to an increase in negative environmental consequences, since pollution is usually caused by the flow of chemicals from agricultural wastewater and industrial enterprises (Kusmambetov & Suleimenova, 2022) (Table 2).

Table 2. Changes in the state of water resources in Kyrgyzstan and Kazakhstan for the period 2014-2024

Indicator	Kyrgyzstan	Kazakhstan
Average water level drop	-8%	-6%
Increased seasonal fluctuations in water levels	+10% variation	+8% variation
Water temperature rise	+1.2°C	+1.0°C
Pollution increase (water quality index)	+15% (increase in the concentration of harmful substances)	+10% (growth in industrial and agricultural wastewater)

Table 2 , Continued

Indicator	Kyrgyzstan	Kazakhstan
Reduced dissolved oxygen concentration	-0.5 mg/L (average reduction of 8%)	-0.3 mg/L (average 5% reduction)
Increased water consumption (agriculture)	+12% compared to 2014	+18% compared to 2014

Source: compiled by the authors based on K.D Kusmambetov & S.Z. Suleimenova (2022), W. Liu *et al.* (2023), G.N. Yusupova *et al.* (2024)

The results of the study indicate the need to introduce adaptive measures in the field of water resources management. In particular, it is recommended to optimise water consumption, modernise irrigation systems, and reduce the anthropogenic load on river basins. This will not only preserve water quality, but also improve the ecological state of water bodies, which is important for ensuring long-term environmental sustainability of the region. In addition, the study highlights the importance of modernising water infrastructure, considering conflicts of interest between different water users, which is crucial for developing effective water management strategies (Yusupova *et al.,* 2024). In addition, economic approaches demonstrate that the introduction of economic incentives can become an effective means of optimising water use, which, in turn, will help to reduce the negative impact on water resources.

Generalisation of findings and analysis of data for 2014-2024 indicate that in order to ensure the sustainability of water resources in Kyrgyzstan and Kazakhstan, it is necessary to implement integrated measures aimed at preserving water quality, modernising infrastructure and optimising water consumption. These measures should consider both natural and anthropogenic factors affecting water resources, which will reduce environmental stress and contribute to the long-term stability of the region.

State of forest ecosystems in Kazakhstan and Kyrgyzstan. The ecological sustainability of forest ecosystems in the region has undergone significant changes under the influence of water resources, which is directly reflected in the area of plantings, forest structure and biodiversity level (Table 3).

Table 3. State of forest ecosystems of Kazakhstan and Kyrgyzstan for the period 2014-2023

Year	Kazakhstan: Forest area, mln. ha	Kazakhstan: Forest-covered land, mln. ha	Kazakhstan: Forested area, %.	Kyrgyzstan: Total Forest area, thous. ha	Kyrgyzstan: Forest area, thous. ha	Kyrgyzstan: Reforestation, thous. ha	Kyrgyzstan: Harvested wood, thous. m³
2014	29.3	12.6	4.6	1,171.8	706.3	1.5	25.0
2015	29.3	12.7	4.6	1,172.0	704.2	2.2	18.1
2016	29.4	12.7	4.7	1,172.0	704.1	3.7	33.2
2017	29.8	12.9	4.7	1,172.0	704.1	2.4	13.7
2018	30.1	12.9	4.7	1,172.0	704.1	2.4	10.3
2019	30.0	13.1	4.8	1,172.0	704.1	2.9	5.3

Table 3, Continued

Year	Kazakhstan: Forest area, mln. ha	Kazakhstan: Forest-covered land, mln. ha	Kazakhstan: Forested area, %.	Kyrgyzstan: Total Forest area, thous. ha	Kyrgyzstan: Forest area, thous. ha	Kyrgyzstan: Reforestation, thous. ha	Kyrgyzstan: Harvested wood, thous. m³
2020	30.0	13.3	4.9	1,172.0	704.1	1.8	9.0
2021	30.6	13.6	5.0	1,171.9	704.0	0.7	6.5
2022	30.9	13.7	5.0	1,171.8	703.9	1.6	11.1
2023	30.9	13.7	5.0	1,171.7	703.9	1.6	12.5

Source: compiled by the authors based on National Statistical Committee of the Kyrgyz Republic (n.d.), Ministry of Ecology and Natural Resources of the Republic of Kazakhstan (n.d.), Bureau of National Statistics (n.d.)

Official data indicate the stability of the total forest fund of Kyrgyzstan, which during 2014-2023 remained at the level of about 1,172 thous. ha. At the same time, the area of land covered with forest decreased from 706.3 thous. ha in 2014 to 703.9 thous. ha in 2023, which raises concerns about the effectiveness of measures to preserve existing forests. Reforestation shows uneven dynamics: if in 2016 this indicator reached a peak (3.7 thous. ha), then in subsequent years the area of new plantings significantly decreased, reaching only 1.6 thous. ha in 2023.

However, independent studies indicate a more alarming state of forest resources. In Kyrgyzstan, water scarcity, which is aggravated by a decrease in the volume of ice cover and unfavourable climatic conditions, led to a reduction in the area of forest stands by 5% over the analysed period. This is especially acute in mountainous areas, where lack of humidity limits the natural processes of forest regeneration. Insufficient water resources lead to a decrease in the density of plantings, slowing down the growth of trees and increasing their vulnerability to pests and diseases, which together leads to a decrease in the number of key tree species by about 10% (Missall *et al.,* 2022). This, in turn, negatively affects the ecosystem functionality of forests, reducing their ability to perform important environmental services such as carbon uptake and biodiversity maintenance. The decrease in the area of forest-covered land may be underestimated due to insufficient monitoring and limited assessment methods. In addition, there is a deterioration in the quality of forests due to damage to stands, which is confirmed by significant fluctuations in wood harvesting. For example, in 2019, this figure was only 5.3 thous. m³, while in 2023 it increased to 12.5 thous. m³, which is partly conditioned by sanitary logging. To prevent further degradation of forest ecosystems in Kyrgyzstan, it is necessary to strengthen monitoring, develop comprehensive forest restoration measures, and improve forest resource management.

Official data show that in Kazakhstan, the total area of land covered with forest increased from 12.6 mln. ha in 2014 to 13.7 mln. ha in 2023, and forest cover remains stable at 5% (Ministry of Ecology..., n.d.). However, these data do not fully reflect the actual state of forest ecosystems, especially in regions suffering from water scarcity, soil degradation and erosion processes, in particular, in the Ili River basin. There is a decrease in the area of forest cover by 7%, which is associated with a complex of factors, including a decrease in the water level, which affects soil moisture, increased erosion processes, and degradation of soil resources. Insufficient moisture caused by a decrease in water reserves leads to a loss of soil fertility, which limits the ability of forests to self-heal. Soil degradation in the Ili River basin leads to a decrease in biodiversity: the number of both endemic and economically important tree species has decreased by 12% (Abayeva *et al.,* 2024; Atantayeva *et al.,* 2024). These changes place an additional burden on the ecological system, as reduced diversity weakens the ability of forest ecosystems to adapt to stressful impacts such as droughts and climate change.

Forest restoration programmes, among which the "Zhasyl El" initiative in Kazakhstan occupies a leading place, demonstrate a certain local efficiency, which explains the increase in total areas covered by forest (Forest Agency of..., n.d.). This programme aims to increase forest cover by planting new plantings and restoring degraded areas. However, at the regional level, the impact of such measures is insufficient to fully compensate for losses caused by water scarcity and erosion processes. In addition, in many regions, there is a need for integrated measures that combine the modernisation of irrigation systems, the use of the latest technologies for monitoring the state of forests and optimisation of water consumption, which would allow for more efficient restoration of forest resources.

Another significant problem is the change in the structure of forest stands. A decrease in water volumes leads to a transition from dense, multi-species forests to sparse forest-steppe formations that are less resistant to external influences. This negatively affects the ability of forest ecosystems to provide important environmental services, such as carbon uptake, biodiversity maintenance, and microclimate management. Changes in the composition of the species fund caused by water scarcity have long-term consequences for regional environmental sustainability, which is enhanced by an increase in anthropogenic load. However, there are positive examples in some areas. According to the latest data, some regions of Kyrgyzstan show gradual restoration of woodlands due to local ecosystem restoration programmes. These programmes include improving irrigation systems, using state-of-the-art monitoring technologies, and specialised forest management, which contributes to the stabilisation or even small growth of forest cover in individual areas. For example, in the Naryn region, the government has introduced a programme for the restoration of forests, which provides for the use of local seedlings and the use of modern technologies for monitoring the state of woodlands (Missall *et al.,* 2022). These measures help not only to restore the area of forest cover, but also improve its quality by optimising irrigation systems and maintaining the water regime, which is critical for biodiversity conservation. However, even these successful local examples cannot compensate for the overall downward trend in forest cover, which requires the development of integrated strategies at the regional level.

Thus, the overall state of forest ecosystems in Kyrgyzstan and Kazakhstan indicates a significant reduction in the area of forest stands and a decrease in the level of biodiversity due to water scarcity and related environmental problems. To ensure the long-term environmental sustainability of the region, it is necessary to implement integrated measures aimed at modernising water infrastructure, optimising irrigation systems, and developing regional forest restoration programmes. Such measures will contribute not only to the restoration of woodlands, but also to the preservation of their ecological functionality, which is critical for maintaining the sustainability of natural systems in the region.

Water resources as a key factor of ecological sustainability of forest ecosystems in Kyrgyzstan and Kazakhstan. Water resources are one of the most important factors determining the ecological sustainability of forest ecosystems. In Central Asian regions such as Kyrgyzstan and Kazakhstan, where water availability is limited by geographical and climatic conditions, the role of water balance in maintaining forest life is becoming critical. Forest ecosystems, in turn, provide a range of ecosystem services, including climate regulation, biodiversity conservation, water intake, and soil stabilisation. Thus, there is a close relationship between the state of water resources and the ability of forests to function as environmentally sustainable systems.

In Kyrgyzstan, water resources play a crucial role in maintaining mountain forests, which are a source of ecosystem services for both local communities and the region as a whole (Kaldybaev *et al.*, 2024). Rivers such as the Naryn form the backbone of the country's water balance, providing the soil moisture needed for trees and other plants to grow. However, due to a decrease in the average water level due to climate changes, there is a gradual reduction in the area of forest cover. Lack of water affects the growth rate of trees, reduces their viability and ability to renew naturally (Yanitskyi, 2024). Combined with the increasing frequency of extreme weather events, such as droughts, this puts additional pressure on forest ecosystems.

In Kazakhstan, the situation is even more critical due to the relatively low water supply and high level of anthropogenic load on water resources. Irrigation systems designed primarily for agricultural needs consume significant amounts of water, reducing its availability to natural ecosystems. For example, in the Ili River basin, a decrease in the water level directly affects the degradation of forests in its floodplain, which are an important component of the region's ecosystem balance (Abraliyev *et al.,* 2024). Such changes lead to an increase in the vulnerability of forests to soil erosion, a decrease in biodiversity, and a decrease in their ability to absorb carbon dioxide.

An important factor that worsens the situation is climate change. An increase in the average annual temperature, a decrease in precipitation, and an increase in its uneven distribution lead to a gradual depletion of water resources (Belmega *et al.*, 2024). This creates a negative feedback loop, where a decrease in the area of forests that serve as natural regulators of the hydrological cycle contributes to an even greater water shortage in ecosystems. This dynamic is particularly noticeable in the semi-desert and steppe zones of Kazakhstan, where woodlands have a limited adaptive capacity for droughts.

Forward-looking estimates show that without effective water management, both countries may face further degradation of forest ecosystems. In Kyrgyzstan, the area of forests is expected to decrease by 5-7% over the next 10 years if the water level drops by 10% (Missall *et al.,* 2022). In Kazakhstan, similar losses can reach 8-10%, especially in regions with a high density of irrigation systems (Abraliyev *et al.,* 2024). Such trends will not only affect environmental sustainability, but will also have serious socio-economic consequences associated with reduced availability of resources for the local population.

To ensure the sustainability of forest ecosystems, it is necessary to implement integrated measures that include effective water management, modernisation of irrigation systems and the creation of water protection zones. In particular, strategic restoration of catchments in the mountainous regions of Kyrgyzstan can help stabilise the water level in rivers. In Kazakhstan, measures to improve the efficiency of water use in agriculture are important, which will increase the availability of water resources for natural ecosystems. In addition, it is necessary to encourage forest restoration through the introduction of adaptive vegetation species that can survive in harsher climates.

Consequently, water resources play a key role in ensuring the ecological sustainability of forests in Kyrgyzstan and Kazakhstan. Their scarcity has a direct negative impact on the functioning of forest ecosystems, creating a threat to their existence in the long term. Considering current trends, immediate measures for the conservation and rational use of water resources are critical to maintaining the viability of forests and preserving their ecological role in the region.

International cooperation water and forest resources management. The management of transboundary water resources is critical for the ecological sustainability of forest ecosystems in Kyrgyzstan and Kazakhstan. Common river basins, such as the Naryn and Ili, require coordination of efforts by both countries to ensure the rational use of water resources and the conservation of biodiversity.

President of Kazakhstan Kassym-Jomart Tokayev announced the creation of the Ministry of Water Resources and Irrigation of the Republic of Kazakhstan (n.d.), a specialised agency that will deal with solving water problems both within the country and in cooperation with neighbouring states. The move underscores Kazakhstan's commitment to sustainable water management and the introduction of green technologies.

Kyrgyzstan and Kazakhstan actively cooperate in the field of water resources management, especially in relation to transboundary rivers. One of the key initiatives is the Law of the Kyrgyz Republic No. 47 "On Ratification of the Agreement between the Government of the Kyrgyz Republic and the Government of the Republic of Kazakhstan on the Use of Interstate Water Management Structures on the Chu and Talas Rivers" (2001). This agreement provides a legal basis for joint management and maintenance of water bodies, ensuring the rational use of water resources and maintaining ecological balance in the basins of these rivers. Within the framework of this agreement, a joint commission has been established that coordinates the actions of both countries in the operation and maintenance of water management facilities. This includes joint monitoring of water resources, exchange of information on hydrological indicators, and coordination of water use plans. Such cooperation contributes to the effective management of water resources and prevents possible conflicts related to their use.

Regarding forest resources, there is currently no information on specific joint programmes between Kyrgyzstan and Kazakhstan. However, both countries are aware of the importance of preserving forest ecosystems and may consider developing joint initiatives in this area. This may include sharing experiences in reforestation, joint research, and developing strategies to adapt forests to climate change. Expanding cooperation in the field of forest resources can be an important step to ensure the ecological sustainability of the region and the conservation of biodiversity. Joint efforts to manage both water and forest resources will contribute to sustainable development and environmental security in both countries.

Investment in infrastructure is also a key element of cooperation. Co-financing projects aimed at improving irrigation systems, water conservation and restoring degraded forest areas will contribute to the sustainable development of both countries. An example of successful international cooperation is the Ukrainian-Romanian partnership in the field of water management, which is implemented within the framework of the Agreement between the Government of Ukraine and the Government of Romania "On Cooperation in the Field of Water Management in Border Waters" (1997), where joint efforts are aimed at rational and environmentally sound use of water and other natural resources of the Danube, Tisa, Prut, and Sirey river basins. The implementation of such initiatives between Kyrgyzstan and Kazakhstan will contribute to strengthening the ecological sustainability of forest ecosystems and ensuring the sustainable development of the region.

Discussion

The results obtained confirm the general trends of changes in the water resources of Kyrgyzstan and Kazakhstan described in the literature. In particular, an analysis of Kyrgyzstan's water resources revealed an 8% decrease in the water level in the Naryn River due to melting glaciers and anthropogenic impact. This is consistent with the conclusions obtained by N.M. Nuralieva (2022), who noted that Kyrgyzstan's glaciers are significantly reduced by climate change, which in the long run reduces the availability of water resources for economic and environmental needs. In Kazakhstan, a 6% decrease in the water level in the Ili River basin and the degradation of coastal ecosystems are consistent with the findings of Y. Yu *et al.* (2021), which indicated a significant impact of human activity, in particular, the intensification of agricultural water consumption and changes in water management at the interstate level. Similarly, K. Orazaliev *et al.* (2024) emphasised that reducing the flow of water from China to the Ili basin, associated with the economic development of Xinjiang, is becoming a key problem for Kazakhstan, creating tension in the use of transboundary waters. The problems of water pollution were also confirmed by A. Tursunova *et al.* (2022). The researchers noted that the increase in industrial and agricultural discharges into water bodies of Kazakhstan and Kyrgyzstan by 10-15% is a consequence of inefficient water resources management and insufficient environmental control.

L. Andersson & E. Ardfors (2021) focused on assessing the possibilities of forest restoration in Kazakhstan, which partially coincides with the results obtained on the ecological sustainability of forest ecosystems. However, unlike the current approach, which considers the impact of water resources on the state of forest ecosystems, this study focuses more on reforestation strategies without a detailed analysis of water supply as a key environmental factor.

The results confirm the importance of integrating water management and environmental policy, as indicated in the literature. B. Sulaimanova *et al.* (2023) considered the role of investment and innovation in the sustainable management of agricultural resources in Kyrgyzstan, in particular, in the context of the green economy. The study focused on the need to invest in the modernisation of irrigation systems and the use of innovative technologies for water conservation. The results support these conclusions, as the degradation of aquatic ecosystems in Kyrgyzstan is largely caused by outdated water management methods that need to be reformed through the introduction of new technologies. The study by S. Giritlioglu & N. Tsoy (2024) emphasised the importance of water security for regional stability by analysing the relationship between Uzbekistan and Afghanistan. It was pointed out that water management in Central Asia is often accompanied by geopolitical tensions that increase the risks of environmental degradation. While the findings focus on Kyrgyzstan and Kazakhstan, they also highlight the impact of transboundary water use on ecosystem degradation. In particular, the reduced flow of water from China to the Ili basin is an example of similar problems that threaten regional stability.

B. Janusz-Pawletta *et al.* (2024) examined the role of stakeholder dialogue in improving water management in Central Asia. The researchers emphasised that effective cooperation between the countries of the region is key to ensuring sustainable water use. The results obtained support this thesis, since the measures proposed in the paper, such as the modernisation of irrigation systems and the creation of water protection zones, require interstate coordination to achieve success. The study by N. Osmonova (2020) was devoted to the analysis of sustainable cooperation in the use of transboundary waters on the example of the Chu and Talas River basins. It was indicated that sustainable development is possible if a balance is achieved between economic needs and environmental requirements. Similarly, the results of the study showed that the growing anthropogenic burden on water resources, both in Kyrgyzstan and Kazakhstan, threatens the ability of forest ecosystems to perform ecosystem functions.

Research by A.N. Rakhimzhanov *et al.* (2021) was devoted to the assessment of the state of turang forests in the south-east of Kazakhstan, which has certain common aspects with the results obtained on the ecological sustainability of forest ecosystems. The main difference is that the researcher focuses on local changes in the structure of forest cover and degradation under the influence of anthropogenic and natural factors, while the current study analyses the relationship between the state of forests and the dynamics of water resources at the broader regional level. A. Aidaraliev *et al.* (2024) highlighted Kyrgyzstan's contribution to solving global problems of sustainable mountain development. Special attention was paid to the need to conserve water resources in the context of growing climate challenges. The results confirm this approach, because the melting of glaciers and the reduction of water resources in Kyrgyzstan, recorded in the study, are key factors affecting the ecological sustainability of the region.

The study by A. Hamidov *et al.* (2022) analysed the integration of the water-energy-food approach to ensure the sustainable development of socio-ecological systems in Central Asia. The researchers emphasise the importance of an interdisciplinary approach for effective management of natural resources, which is also relevant for the Naryn and Ili River basins considered in the study. The results confirm that water scarcity negatively affects not only ecosystems, but also food security, which requires a comprehensive approach to developing adaptation strategies. E. Ahmadov (2020) considered the issues of water resources management for achieving sustainable development in Azerbaijan. The researcher focused on the need for rational use of water resources, modernisation of water infrastructure, and creation of water protection zones. This supplements the conclusions of this study, which also suggest the modernisation of irrigation systems and the creation of protected areas to preserve environmental sustainability.

In turn, the study by S. Kitaibekova *et al.* (2023) evaluated forest ecosystem services in "Burabai" national park, which provides valuable information about the socio-economic significance of forest ecosystems. Compared to the results obtained, which focus on the ecological aspects of the impact of water resources on forest ecosystems, this study is more focused on the economic assessment of ecosystem services, which complements the study, adding a practical perspective on the use of forest resources. Thus, the results confirm the conclusions of previous studies, emphasising the need for integrated water management, modernisation of irrigation systems, and adaptive reforestation to ensure the ecological sustainability of the region. The results of the study specify the scale of changes, in particular quantitative losses of water and forest resources, which complements the available literature with new data.

Conclusions

Analysis of the water resources of Kyrgyzstan and Kazakhstan for the period 2014-2024 revealed significant changes in water supply and water quality. In Kyrgyzstan, the average water level in the main rivers, in particular in Naryn River, decreased by 8% compared to the beginning of the study. This is conditioned by the intense melting of glaciers due to an increase in average annual temperatures, which leads to a decrease in the ice sheet and long-term water reserves. Anthropogenic impact, in particular, water intake for irrigation and hydropower, worsens the situation. Increasing the average summer water temperature by 1.2°C reduces the concentration of dissolved oxygen, negatively affecting the chemical composition of water and biodiversity. River pollution from industrial and agricultural discharges has increased by 15% over the past decade. In Kazakhstan, there is a similar trend: the water level in the Ili River basin decreased by 6% during the analysed period. This is conditioned by an increase in domestic water consumption, especially in agriculture, and a reduction in water inflows from China due to the intensive use of resources for Xinjiang's development. The decline in the water level in Lake Balkhash, which depends on the Ili River, has led to the degradation of coastal forests, reduced biodiversity and salinisation of soils. A 1.0°C increase in the lake's water temperature and a 10% increase in pollution exacerbate the negative environmental impacts, as the pollution is caused by chemicals from agricultural and industrial runoff.

The forest ecosystems of Kazakhstan and Kyrgyzstan are significantly affected by water scarcity and climate change. In Kyrgyzstan, a 5% reduction in forests is caused by melting glaciers and reduced humidity, which complicates their regeneration, reduces biodiversity and weakens ecosystem functionality. In Kazakhstan, a 7% decrease in forest area, in particular in the Ili River basin, is associated with a decrease in water levels, soil degradation, and loss of species diversity (by 12%). Positive local initiatives, such as the "Zhasyl El" programme in Kazakhstan and the restoration of forests in Kyrgyzstan, have limited impact. Long-term sustainability requires comprehensive strategies: water management modernisation, irrigation optimisation, and the introduction of modern natural resource management technologies.

The analysis shows that the water balance directly affects biodiversity conservation, soil stability, and the ability of forests to perform their ecosystem functions. The conditions of limited water availability typical of Central Asia are compounded by climate change, which leads to a decrease in water resources, a reduction in forest areas, and an increase in their vulnerability to degradation. In Kyrgyzstan, the biggest challenges relate to mountain forests, which depend on the stability of the river catchment area, while in Kazakhstan, significant pressure is caused by irrigation systems that reduce the availability of water for natural ecosystems.

Increasing water scarcity creates negative feedback, where reducing the area of forests increases water stress in the region. Projected forest cover losses over the next decade indicate the need for immediate action to mitigate this impact. Effective water management, modernisation of irrigation systems, creation of water protection zones and introduction of adaptive reforestation methods can help to stabilise the ecological balance. Strategic measures are aimed not only at preserving forest ecosystems, but also at ensuring their role as regulators of the hydrological cycle, which is important for the socio-economic well-being of the region.

International cooperation in water and forest management is key to ensuring environmental sustainability in Kyrgyzstan and Kazakhstan. The joint management of transboundary water resources, in particular the Naryn and Ili rivers, promotes water management and prevents environmental problems. The agreement between the governments of both countries on the use of water management facilities on the Chu and Talas rivers is an important step for sustainable water use. The development of collaborative forest resource initiatives, in particular, research and adaptation strategies, will contribute to biodiversity conservation and ecosystem improvement. Investment in infrastructure and adaptation to climate change will help to improve environmental security and sustainable development in the region.

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Conflict of Interest

None.

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Анотація. Актуальність дослідження зумовлена зростаючим впливом зміни клімату та антропогенного навантаження на водні ресурси, які мають вирішальне значення для підтримання екологічної стійкості лісових екосистем Центральної Азії. Метою дослідження було оцінити зміни водних ресурсів Киргизстану і Казахстану протягом 2014-2024 рр. та визначити їх вплив на екологічну стійкість лісових екосистем. Методи дослідження включали аналіз гідрологічних даних щодо кількості та якості водних ресурсів за вказаний період, а також аналіз наукових джерел щодо взаємозв'язку між водним балансом, біорізноманіттям та станом ґрунтів. Зокрема, було проаналізовано рівень води у великих річках (Нарин, Ілі), зміни температури води, хімічне забруднення та динаміку лісових площ. Результати показали, що рівень води в річці Нарин знизився на 8 % через танення льодовиків і збільшення водозабору, в той час як в річці Ілі цей показник склав

6 % через зменшення припливу води з Китаю і збільшення водоспоживання. Середня температура води зросла на 1,0-1,2°C, що призвело до зниження концентрації розчиненого кисню та негативно вплинуло на біорізноманіття. Забруднення води промисловими та сільськогосподарськими скидами зросло на 10-15 %, що посилило деградацію прибережних екосистем та біорізноманіття. Дані свідчать про відносну стабільність загального лісового фонду Киргизстану, але спостерігається зменшення площі земель, вкритих лісом, що викликає занепокоєння щодо ефективності природоохоронних заходів. Лісовідновлення демонструє нестабільну динаміку через зміну клімату та дефіцит води. Скорочення лісових площ склало 5 % у Киргизстані та 7 % у Казахстані, причому найбільші втрати спостерігаються в басейні річки Ілі. Зменшення біорізноманіття в Казахстані досягло 12 %, а в Киргизстані скорочення площі лісів посилило водний стрес у гірських регіонах. Отримані дані підкреслюють тісний взаємозв’язок між станом водних ресурсів і здатністю лісових екосистем виконувати екологічні функції

Ключові слова: зміна клімату; біорізноманіття; біогеоценоз; річкові басейни; рослинність

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