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Symptoms of *Fraxinus excelsior* damage in Zhytomyr Polissya

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Abstract. Common ash (*Fraxinus excelsior* L.) is an important part of the forest, shelterwood and ornamental stands. The health status of *F. excelsior* has recently deteriorated in many regions, due to climate change, anthropogenic stress, diseases and phytophagous insects. The effects of these factors are manifested in symptoms, the prevalence and severity of which depend on local conditions, in particular forest site conditions, stand composition, and structure. The aim of the

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research was to identify the forest site conditions and other stand characteristics most favourable for the prevalence and severity of symptoms of ash decline in Zhytomyr Polissya. The tasks were: to evaluate the common ash health condition, the symptoms of its decline, and their prevalence and severity in relation to forest category, forest site conditions, main forest forming tree species, ash origin, age, and relative stocking density. The majority of the ash stands surveyed were found to be weak. The health condition of *F. excelsior* deteriorates with age. It is worse in forest belts, in damp relatively fertile forest site conditions (C_4), in the stands of vegetative origin, with a lower relative stocking density, and in the stands with *Alnus glutinosa* as the main forest forming species. Dry branches, epicormic shoots, collar rot, and ash bark beetles were the most common symptoms of ash weakness. The prevalence and severity of most of these symptoms were the highest in the forest shelter belts, in the damp relatively fertile forest site conditions (C_4), in the stands of vegetative origin, with a lower relative density of stocking and older than 60 years. It is necessary to monitor the health status of *F. excelsior* in order to detect pathological processes and to select trees for selective sanitary felling in time. The severity of collar rot increased at the relative stocking density of 0.8. It was proposed to grow *F. excelsior* in mixed stands mainly with *Quercus robur* and to give preference to seed origin. It is necessary to monitor the health status of *F. excelsior* in order to detect pathological processes and to select trees for selective sanitary felling in time

Keywords: tree health condition; dry branches; epicormic shoots; collar rot, bark beetles; prevalence (of symptoms); severity (of symptoms)

Introduction

Ash trees are key species in forest plantations in the Zhytomyr Polissia region, and their health plays a crucial role in maintaining the ecological balance of local forest ecosystems. Damage to these trees can signal alarming changes in the ecosystem, caused by both biotic (pests, diseases) and abiotic factors (climate change, environmental pollution) factors. Identifying and analysing damage symptoms allows for the timely diagnosis and control of diseases and pests, thus contributing to the conservation of ash populations in Polissia. This is particularly important in the context of the spread of dangerous pathogens, such as the emerald ash borer, which has already caused significant damage to ash trees in Europe. Research into damage symptoms will also help to develop effective methods for protecting and restoring forest plantations, which supports the preservation of biodiversity and enhances the resilience of

forest ecosystems to external stresses. The conservation of *Fraxinus excelsior* is also of economic importance, as these trees are valuable for forestry and can be used in various industries.

The health status of Common ash (*Fraxinus excelsior* L.) has deteriorated in many regions, due to climate change and anthropogenic stress, which has increased the susceptibility of trees to biotic damage. N. La Porta *et al.* (2022) provide an overview of the main bacterial pathogens of trees, the current methods of bacteria detection, and the efforts to increase tree resistance.

Ash dieback (caused by *Hymenoscyphus fraxineus*) is widespread in many European countries. M.K. Horáková *et al.* (2023) determined the prevalence of ash dieback in Slovakia using species-specific primers. Infected trees were detected in different stands, wherever the host was present.

Mixed infestations of the same trees with different pests and pathogens have been reported in many regions. S. Peters *et al.* (2023) in Germany found a fungal pathogen (*Armillaria* sp.) in the stem collar necrosis without the presence of *H. fraxineus*. In the next study, these authors S. Peters *et al.* (2024) analysed interactions of multilocus genotypes (MLGs) of *H. fraxineus* with other fungi from stem collar necroses. In six German federal states, L. Lysenko *et al.* (2024) analysed the prevalence of fungal communities, including *H. fraxineus*, in soil and fine roots. They estimated a higher diversity in soil samples than in root-associated samples.

R. Vasaitis (2024) mentioned two alien invasive pathogens and pests of ash trees in Ukraine: the fungus *Hymenoscyphus fraxineus*, and the xylophagous beetle *Agrilus planipennis*. The area of *A. planipennis* invasion comprised 13.3 hectares in 2019 in the Luhansk region, expanding to 1211.7 hectares in the Luhansk, Kharkiv, and Kyiv regions by 2023. Infested trees are often colonised by bark beetles *Hylesinus crenatus* and *H. varius*. Observations by B. Laz (2024) in Turkey showed that 28 % of the ash trees (*Fraxinus angustifolia* Vahl) were infested by *Zeuzera pyrina* L. (Lepidoptera: Cossidae).

V. Meshkova *et al.* (2021) confirmed the presence of ash dieback by molecular methods in samples from different natural zones of Ukraine, except for the southern regions. The prevalence of ash dieback among other factors of ash weakening was investigated in geographical provenance tests in the Sumy region. A. Goychuk *et al.* (2022) identified the causes of forest deterioration in Zhytomyr Polissya, and studied the aetiology and pathogenesis of ash diseases. An increase in the prevalence of typical symptoms of bacterial diseases, dieback, vascular (graphiosis, tracheomycosis), and fruiting bodies of wood-destroying fungi was observed. Bacterial disease and dieback were the most acute pathological processes.

A. Goychuk *et al.* (2023) characterise the typical symptoms, pathogenesis, and causal agents of bacterial diseases affecting forest trees in Ukraine, in particular of *Fraxinus excelsior* caused by *Pseudomonas syringae* pv. *savastanoi*. Infection has been shown to damage trees when they are two or three years old, affecting stems, branches, shoots, and inflorescences. However, the disease can only be diagnosed when tumours have formed. The data obtained provide an approach for effective disease detection and plant protection. V.L. Borysova (2021) studied the health of common ash in the Left-bank Forest Steppe of Ukraine and evaluated the prevalence of the foliage-damaging insects, bark beetles, wood-destroying fungi, bacteriosis, and ash dieback in the Kharkiv, Sumy, and Poltava regions, taking into account weather, forest site and stand characteristics.

To prevent the deterioration of ash stands the researchers have focused on identifying the direct and indirect causes of ash decline and the main symptoms for their detection in monitoring programmes. Remote sensing technologies can help to obtain fast and repeated information on ash damage on a large spatial scale. M. Gašparović *et al.* (2023) described the monitoring of ash dieback using remote sensing technologies. However, such an approach was effective in Croatia only for narrow-leaved ash, which forms homogeneous forest stands. Therefore, the ground survey remains the most reliable method of forest health monitoring.

The aim of the research was to identify the forest site conditions and other stand characteristics most favourable for the prevalence and severity of symptoms of ash decline in Zhytomyr Polissya. The tasks were: to evaluate the common ash health, the symptoms of its decline, and their prevalence and severity in relation to forest category, forest site conditions, main forest forming tree species, ash origin, age, and relative stocking density.

Materials and Methods

The field research was carried out in 2023 in the forests of the Branch “Zvyagelske Forestry” (Ukraine). The climate was moderately continental and favourable for the growth of trees and shrubs characteristic of the forest vegetation zone (Buzun *et al.*, 2018). In order to select the sub-compartments for sample plots, the database of the Ukrainian State Forest management Planning Association (n.d.) was analysed. As the main forest forming species, common ash grew only on 2.5 ha, but it grew in composition with English oak (*Quercus robur* L.) and Black alder (*Alnus glutinosa* L.) on 180 ha. most of the ash stands were located in the Horodnytsky Forestry.

Among ash sub-compartments, there were three stand categories (forest greenery, commercial forest, and forest shelterbelts), three forest site conditions (moist relatively fertile – C₃; moist relatively fertile – D₃, damp relatively fertile – C₄), three main forest forming tree species (*A. glutinosa*, *Q. robur*, and *F. excelsior*), different origin (vegetative, natural seed and planted seed), age (<30; 31-60, and >60 years) and relative stocking density (0.6, 0.7, and 0.8) were chosen. Fourteen sample plots were laid. For twenty ash trees in each sample plot, the health condition class and the symptoms of ash damage (dry branches, epicormic shoots, collar rots, and bark beetle infestation) were selected.

The health condition class was assessed visually according to the Resolution of the Cabinet of Ministers of Ukraine No. 756 (2016): I – healthy; II – weakened; III – severely weakened; IV – desiccated; V – recently diseased; VI – diseased more than one year ago. For each sample plot, two health condition indices were evaluated: HCI₁₋₆ – for all trees (living and dead) and HCI₁₋₄ (only for living trees) (Guidelines ..., 2020). The prevalence of dry branches, epicormic shoots, collar rots, and bark beetle

infestation was estimated as the percentage of trees with the given symptoms in each sample plot.

The prevalence of bark beetles was estimated by the presence of entry or exit holes in the bark in the lower 2 m of the tree. The tree was considered infested if at least one hole was detected. Dry branch severity was scored as a percentage for each tree and then converted into points: 0 – 0%; 1 point – <10%; 2 points – 11-50%; 3 points – 51-75%; 4 points – >75% (Guidelines ..., 2020). The severity of epicormic shoots was scored in three classes: 1 point – single; 2 points – abundant; 3 points – total stem coverage. Collar rot severity was scored in four classes according to the spread of necrosis: 0 – absent; 1 point – <25% of circumference; 2 points – 26-50% of circumference; 3 points – 51-75% of circumference; 4 points – >75% of circumference (Guidelines ..., 2020).

Microsoft Excel and the statistical software package PAST (Hammer *et al.*, 2001) were used for data analysis and visualisation. Prevalences of symptoms were compared using a z-test (Peck *et al.*, 2020). The difference between the proportions was considered significant for P = 0.05 at Z > 1.96. The study met the ethical standards of the Convention on Biological Diversity (1992) and the Convention on the Trade in Endangered Species of Wild Fauna and Flora (1973).

Results and Discussion

The surveyed stands represent forest green areas, commercial forests, and forest shelter belts. The health condition of *F. excelsior* is the best in forest green areas and worst in the forest shelter belts (Fig. 1a). According to the HCI, which considers all living and dead trees (HCI₁₋₆), the inspected ash trees are “weakened” and according to the HCI, which considers only living trees (HCI₁₋₄), the stands are “healthy”. Dry branches in the crown were the most common symptoms of tree weakness (Table 1).

Table 1. The prevalence of certain symptoms of *F. excelsior* weakness in the different stand categories

Stand categories	Prevalence, %			
	Dry branches	Epicormic shoots	Collar rot	Bark beetles
Forest green areas	83.6 ± 3.70a	32.5 ± 4.68a	11.3 ± 3.16a	4.5 ± 2.07a
Commercial forest	84.6 ± 3.61a	38.1 ± 4.86ab	13.1 ± 3.38a	7.3 ± 2.59a
Forest shelter belts	86.5 ± 3.42a	51.5 ± 5.00b	20.0 ± 4.00a	8.5 ± 2.79a

Note: letters show significant differences inside each column at $p < 0.05$

Source: developed by the authors

The lowest proportion of trees with dry branches was found in the forest green areas and the highest in the forest shelter belts. Epicormic shoots, collar rot, and bark beetle infestation were also the most common in the shelter belts but less common than dry branches (Table 1).

The severity of “dry branches” increased from forest green areas to forest shelter belts (Fig. 2a). The severity of epicormic shoots and collar rots was also highest in shelter belts. Ashes have the worst health in the damp relatively fertile forest site conditions (C_4), where both health condition indices are characteris-

tic of weakened trees (Fig. 1b). Tree health in the moist relatively fertile forest site conditions (C_3) was slightly better than in the moist fertile forest site conditions (D_3). However, both health condition indices assess tree health between “healthy” and “weakened”.

Dry branches dominate among damage symptoms (Table 2). Dry branches, epicormic shoots, collar rot, and bark beetle infestation were the most common in the damp relatively fertile forest site conditions (C_4) and least common in the moist relatively fertile forest site conditions (C_2).

Table 2. The prevalence of certain symptoms of *F. excelsior* weakness in the different forest site conditions

Forest site conditions	Prevalence, %			
	Dry branches	Epicormic shoots	Collar rot	Bark beetles
C_3	83.6 ± 3.70a	32.2 ± 4.67a	11.1 ± 3.14a	5.3 ± 2.25a
C_4	86.7 ± 3.40a	52.0 ± 5.00b	19.5 ± 3.96a	9.8 ± 2.97a
D_3	84.8 ± 3.59a	40.0 ± 4.90ab	12.0 ± 3.25a	6.0 ± 2.37a

Note: letters show significant differences inside each column at $p < 0.05$

Source: developed by the authors

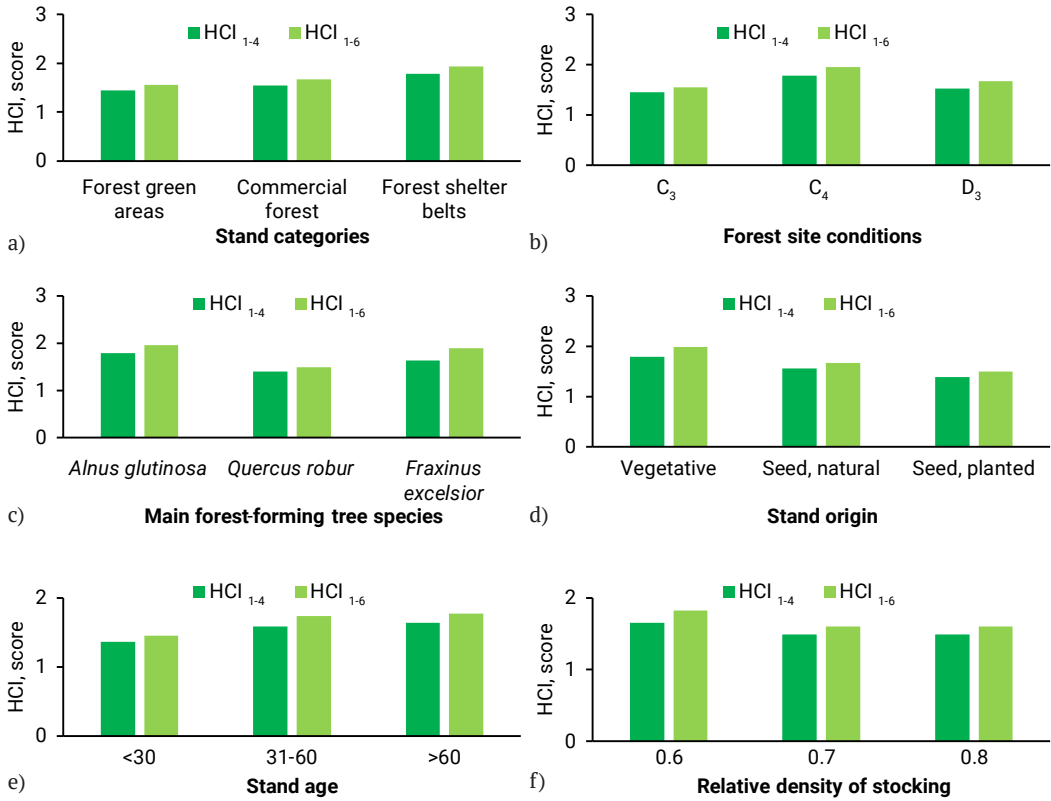


Figure 1. Health condition index of *F. excelsior* depending on site and stand parameters

Note: HCl₁₋₄ – health condition index for the trees of the 1st-4th classes of health condition; HCl₁₋₆ – health condition index for the trees of the 1st-6th classes of health condition; site and stand parameters: a) stand categories; b) forest site conditions; c) main forest-forming tree species; d) stand origin; e) stand age; f) relative density of stocking

Source: developed by the authors

The severity of most symptoms of tree damage was also the highest in the damp relatively fertile forest site conditions (C₄) and the

lowest in the moist relatively fertile forest site conditions (C₃) (Fig. 2b). The severity of collar rot was the same in C₃ and D₃.

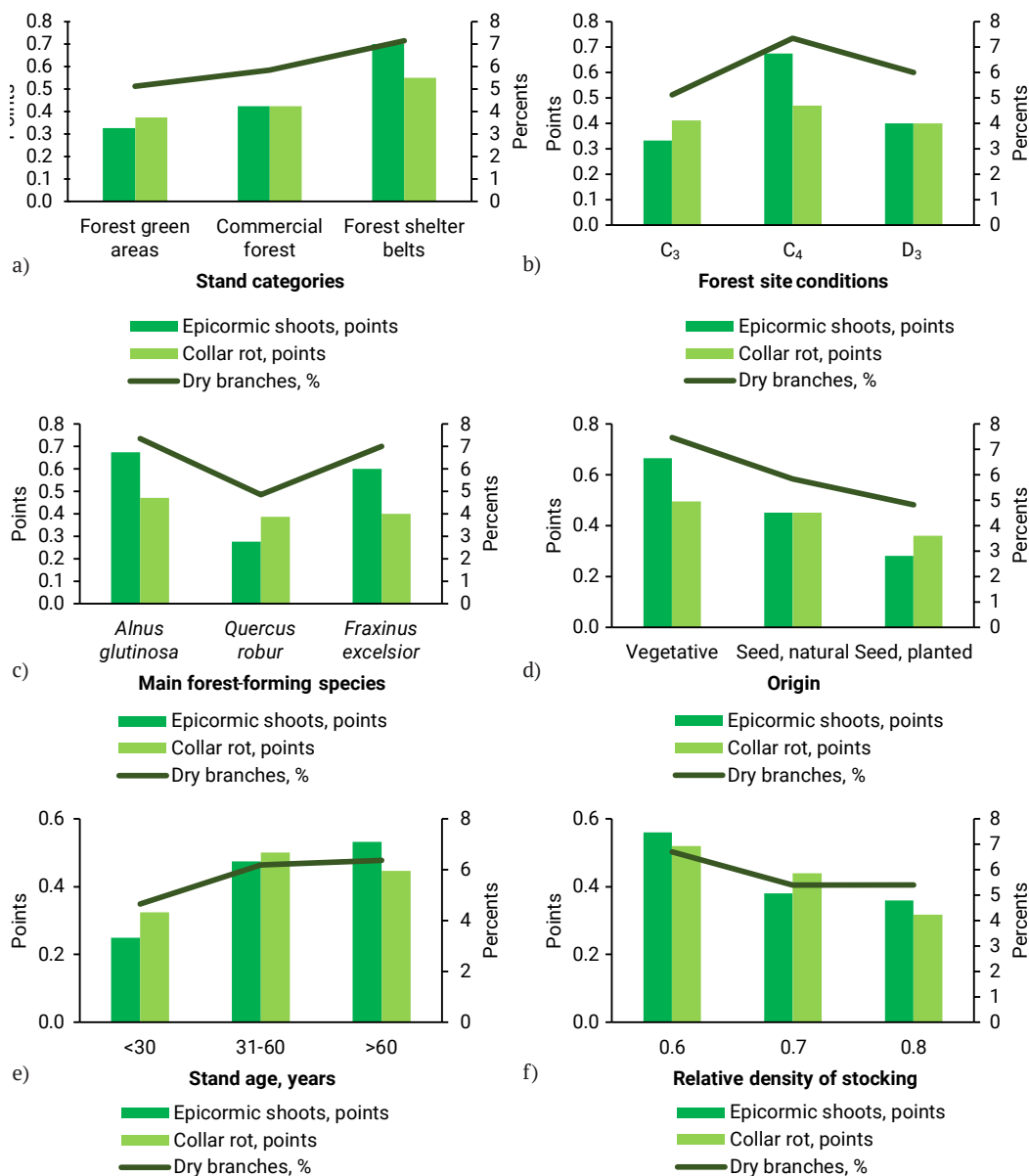


Figure 2. Severity of some symptoms

of *F. excelsior* deterioration in relation to site and stand parameters

Note: site and stand parameters: a) stand categories; b) forest site conditions; c) main forest-forming tree species; d) stand origin; e) stand age; f) relative density of stocking

Source: developed by the authors

The health of ash was worst in the forest stands with Common alder (*A. glutinosa*) as

the main forest forming species (Fig. 1c). However, even in these stands, the health condition

index of ash does not exceed 2 points. In the stands with English oak (*Q. robur*) the difference between the two health indices is minimal ($HCI_{1-6} = 1.5$; $HCI_{1-4} = 1.4$), and in the stands with *F. excelsior* this difference is maximal ($HCI_{1-6} = 1.9$; $HCI_{1-4} = 1.6$).

Dry branches in ash trees were the most common in the forest stands with different main forest forming species (Table 3). The proportion of ash trees with dry branches exceeded 80% in all stand groups and was lowest in the stands with oak as the main forest forming species.

Table 3. The prevalence of certain symptoms of *F. excelsior* weakness in the different forest forming species

Forest forming species	Prevalence, %			
	Dry branches	Epicormic shoots	Collar rot	Bark beetles
<i>Alnus glutinosa</i>	86.7 ± 3.40a	52.0 ± 5.00b	19.5 ± 3.96b	9.8 ± 2.97a
<i>Quercus robur</i>	83.2 ± 3.74a	29.4 ± 4.55a	9.3 ± 2.90a	5.3 ± 2.23a
<i>Fraxinus excelsior</i>	86.0 ± 3.47a	50.0 ± 5.00b	20.0 ± 4.00b	6.0 ± 2.37a

Note: letters show significant differences inside each column at $p < 0.05$

Source: developed by the authors

The prevalence of trees with epicormic shoots, collar rot and bark beetle attack was lowest in stands with oak as the main forest forming species (Table 3). The severity of ash damage symptoms was also minimal in oak stands (Fig. 2c). However, the severity of collar rot was similar in the forest stands with oak and ash as the main forest forming species (0.4 points) and lower than in alder stands (0.5 points). *F. excelsior* was present in forest stands of vegetative, natural seed, and planted seed origin. The ash trees of vegetative origin had the worst condition ($HCI_{1-6} = 2.0$; $HCI_{1-4} = 1.8$), the trees of planted seed

origin had the best condition ($HCI_{1-6} = 1.9$; $HCI_{1-4} = 1.6$) (Fig. 1d).

The prevalence of certain symptoms of ash damage was also the highest in the vegetative stands and the lowest in the planted seed stands (Table 4). However, the prevalence of dry branches exceeded 80% in all origins. The prevalence of ash trees with epicormic shoots in seed stands was significantly lower than in the stands of vegetative origin. The prevalence of collar rot and bark beetle infestation was also the highest in vegetative stands, with a significant difference only for collar rot between vegetative and planted seed stands.

Table 4. The prevalence of certain symptoms of *F. excelsior* weakness depending on the forest stand origin

Stand origin	Prevalence, %			
	Dry branches	Epicormic shoots	Collar rot	Bark beetles
Vegetative	86.8 ± 3.38a	53.3 ± 4.99a	21.3 ± 4.10b	9.3 ± 2.91a
Seed, natural	84.6 ± 3.61a	38.8 ± 4.87b	13.7 ± 3.43ab	6.2 ± 2.41a
Seed, planted	83.2 ± 3.74a	29.0 ± 4.54b	8.8 ± 2.83a	5.6 ± 2.30a

Note: letters show significant differences inside each column at $p < 0.05$

Source: developed by the authors

Despite the high prevalence of dry branches in the crowns of ash trees, the severity of this symptom was relatively low. At the same time,

according to this indicator, the same regularity was found – the greatest severity of dry branches in trees of vegetative origin and the least –

in trees of planted seed origin (Fig. 2d). The severity of epicormic shoot development also decreased in ash trees from vegetative to seed origin (Fig. 2d).

Considering the uneven distribution of ash stands by age classes, all surveyed stands were divided into three age intervals for the assessment of tree health and the prevalence and severity of individual symptoms: up to 30

years, 31-60 years and over 60 years. The HCI increased with age (Fig. 1e). According to HCI₁₋₄, ash stands up to 30 years old can be considered healthy. At the same time, by HCI₁₋₆, such stands are weakened. Stands older than 30 years are weakened when considering both viable and all ash trees. The prevalence of dry branches tended to increase with age but without significant differences between age groups (Table 5).

Table 5. The prevalence of certain symptoms of *Fraxinus excelsior* weakness in different age groups

Age, years	Prevalence, %			
	Dry branches	Epicormic shoots	Collar rot	Bark beetles
≤ 30	83.0±3.76a	27.5±4.47a	8.0±2.71a	5.8±2.33a
31-60	85.0±3.57a	42.0±4.94b	15.5±3.62a	6.0±2.37a
> 60	85.3±3.54a	43.3±4.96b	16.0±3.67a	7.7±2.66a

Note: letters show significant differences inside each column at $p < 0.05$

Source: developed by the authors

The prevalence of epicormic shoots, collar rot, and bark beetle infestation also increases with age. However, the differences are significant only for epicormic shoots (Table 5). The severity of dry branches and epicormic shoots also increases with age (Fig. 2e). However, the severity of collar rot over 60 years is less than in 31-60 years. At all levels of relative stocking

density (0.6-0.8), the HCI indicates tree weakness (Fig. 1f). The stands with the lowest relative stocking densities had the poorest health. The prevalence of dry branches, epicormic shoots, collar rot, and bark beetle infestation tended to decrease with increasing stocking density of ash stands (Table 6). However, these differences are not significant.

Table 6. The prevalence of certain symptoms of *F. excelsior* weakness at different relative stocking densities

Relative stocking density	Prevalence, %			
	Dry branches	Epicormic shoots	Collar rot	Bark beetles
0.6	85.7±3.50a	46.2±4.99a	17.2±3.77a	7.2±2.58a
0.7	84.0±3.66a	35.0±4.77a	12.0±3.25a	5.2±2.22a
0.8	84.1±3.66a	34.4±4.75a	11.2±3.15a	7.4±2.62a

Note: letters show significant differences inside each column at $p < 0.05$

Source: developed by the authors

The severity of dry branches, epicormic shoots, and collar rot also tended to decrease with increasing relative stocking density of ash stands (Fig. 2f). Thus, the assessment of

common ash health and symptoms of its deterioration confirms the dependence of their prevalence and severity on stand category, forest site conditions, main forest forming

tree species, ash origin, age, and relative stocking density.

Tree health has deteriorated in many regions. The most common approach is to assess the degree of ecosystem degradation. J. Maes *et al.* (2023) assessed the health of forest ecosystems in Europe on a scale from 0 (degraded ecosystem) to 1 (pristine or protected forest). One third of the forest area was found to be in decline.

In order to prevent forest degradation and mitigate its consequences, forest health is monitored by the condition of the crown and trunk and some specific signs that allow the identification of the pest or pathogen. According to the Resolution of the Cabinet of Ministers of Ukraine No. 756 (2016), the main criterion for sanitary felling is the tree health class. However, all trees (living and dead) are included in the calculation of the health condition index, which does not show the dynamics of tree mortality. In the present study, both health condition indices (HCI_{1-4} for living trees and HCI_{1-6} for all trees) were calculated and compared for different site and stand parameters: stand categories; forest site conditions; main forest forming tree species; stand origin; stand age; relative stocking density (Fig. 1).

European monitoring programmes assess defoliation and discolouration to compare the dynamics of trees and stand health in various regions (Manual..., 2010). In Ukraine, extensive forest monitoring (I Level), harmonized with the European ICP Forest monitoring programme (Manual..., 2010), has been carried out for 30 years. monitoring data on the health of *Fraxinus* sp. in Ukraine for 15 years have been analysed by T. Pyvovar *et al.* (2022). The highest degree of defoliation was observed in the Steppe zone, the most acute tree mortality in the forest zone, and the most stable health condition in the Forest-Steppe zone. Of all the ash trees surveyed in Polissya, 42% were damaged,

with diseases dominating. This was explained by the wetter climate of the forest zone compared to the Forest Steppe and Steppe zones. In the forest-steppe zone, almost half of the ash damage (48.2%) was caused by abiotic factors. At the same time, in the forest-steppe zone, pathogen damage to ash increased by 21.9% over 15 years, reaching 56% in 2011-2015. In the steppe zone, insects were the main cause of damage to ash trees. The prevalence of trees with ash dieback increased from the forest to the steppe zone, and the prevalence of bacteriosis decreased from the forest to the steppe zone. The prevalence of wood-destroying fungi on ash was the highest in the forest-steppe zone, and of tuberculosis – in the forest and forest-steppe zones.

New pests and diseases have spread. An emerald ash borer (*Agrilus planipennis* Fairmaire, 1888 (Coleoptera: Buprestidae)), originating from Asia, invaded North America and Russia at the end of the 20th century and was discovered in the Luhansk region of Ukraine in 2019 and is already present in Kyiv in 2024 (State Service of Ukraine..., 2024). J. Sun *et al.* (2024) describe the seasonal development of this pest, its characteristics, and tree damage. The larvae develop under the bark and gradually gnaw through the conductive tissues, often bringing pathogens into the tree, leading to tree mortality. They mentioned the importance of searching for resistant trees for more effective forest protection. So-called ash dieback was discovered in Europe in the 1990s. E. Baxter *et al.* (2023) in Ireland described its symptoms – reduction of tree increment, leaf size, discolouration and premature leaf fall, appearance of ulcers on the trunk and shoots, and dieback of small branches. Therefore, assessing defoliation alone is not enough to know the health of a tree.

V. Meshkova *et al.* (2021) studied the prevalence of ash dieback among other factors of ash deterioration in geographical provenance

tests in the Sumy region. Root rot, ash dieback, and infestation by ash bark beetle (*Hylesinus crenatus* (Fabricius, 1787): Coleoptera: Scolytidae) were found in all proveniences. Root rot was found in all ash proveniences. The ash bark beetle was not found in the proveniences from the Western and Right Bank Forest Steppes. *Hymenoscyphus fraxineus* was isolated from the trunks of ash trees, and identified by molecular methods and confirmed to be pathogenic. For seven years, the health condition index, incidence, and severity of ash dieback increased in all proveniences except the Steppe.

In the current study, the prevalence and severity of dry branches, epicormic shoots, collar rot, and bark beetles were compared for different site and stand parameters: stand categories; forest site conditions; main forest forming tree species; stand origin; stand age; relative stocking density (Fig. 2). The health status of *F. excelsior* was best in green forest areas and worst in forest shelterbelts. This can be explained by the negative impact of timber harvesting on all components of forest ecosystems, especially the soil, the trees, and the regeneration of the forest. I.C. Cântar *et al.* (2022) monitored the health of remaining trees after logging in Romania to determine the tolerance threshold of trees to logging. They developed equations taking into account the relationship between the size of the healed damage and the diameter of the trees.

S.V. Sydorenko *et al.* (2020) studied the protective forest belts in the Kharkiv region (Ukraine). According to their health status, the forest shelterbelts were characterised as weakened and severely weakened. Among the pests, 23 xylophagous and 21 phyllophagous insect species were identified. However, most of them can only colonize weakened and severely weakened trees. The study showed that the combined effect of the absence and neglect of forestry and agrotechnical interventions in

the shelterbelts caused partial tree mortality, resulting in the spread of pathogens and insect pests that invaded individual trees in the forest stands. O.A. Kuznetsova *et al.* (2023) assessed such symptoms of decline of *Ulmus* sp. together with some specific indicators which made it possible to establish the characteristics of the spread of bacterial and fungal diseases, and bark beetles in shelter belts along the Kyiv-Kharkiv highway.

In the current survey dry branches in the crowns were the most common symptoms of tree weakening (Table 1). It is known that dry branches can be the result of various causes. S.V. Sydorenko *et al.* (2020) found maple trees with dry branches remaining in the crowns in shelterbelts restored after verticilliosis. Long-term retention of dry branches in the crown leads to the classification of such trees as severely weakened or even desiccated, while the crown gradually recovers. An objective assessment of tree health can only be made after several years of monitoring.

Ash dieback is the most serious disease affecting *Fraxinus* sp. in different regions and stands. It is named after the appearance of dry branches in the crowns. A. Benigno *et al.* (2023) in Central-Northern Italy found that the severity of ash dieback was higher in sites under environmental stress (mild dry winters, and hot dry summers) or anthropogenic stress (logging and fires).

In the present study, ashes were least healthy in the damp relatively fertile forest site conditions (C_4), where both health condition indices were characteristic of weakened trees (Fig. 1b), and in the forest stands with common alder (*Alnus glutinosa*) as the main forest-forming species (Fig. 1c). However, under wetter conditions, alder was the dominant species. V. Borysova (2021) studied the health status of common ash in the Left-bank Forest Steppe of Ukraine. In her sample plots, the prevalence

of symptoms depended on the cause of the pathology, the type of forest site conditions, and some other forest characteristics. For example, ash dieback was prevalent in fresh fertile forest site conditions and bacteriosis was prevalent in the fresh fertile, humid fertile, and humid relatively fertile forest site conditions.

In the current survey, the prevalence of trees with dry branches, epicormic shoots, collar rot and bark beetle infestation was the lowest in the stands with oak as the main forest forming species (Table 3). However, the severity of collar rot was similar in the forest stands with oak and ash as the main forest forming species (Fig. 2c). This may be explained by the dependence of collar rot severity on soil moisture. G.J. Langer *et al.* (2022) within the FraxForFuture project show that soil moisture promotes the prevalence and severity of collar rot caused by *Phytophthora*, *Armillaria* and ash dieback. These pathogens often occur together and it is sometimes difficult to determine the primary cause of tree decline.

The poorest health of vegetative origin trees in the current survey (Fig. 1d) may be explained by the younger age of the planted trees, which were in the best health (Fig. 1e). The prevalence of most symptoms of tree decline increased with the age of the ash, except for collar rot (Fig. 2e). Such trees are easily detected and could be removed by selective sanitary felling in previous years.

As forest health continues to decline, it is important to identify disease-resistant trees and propagate their progeny for planting in new forests. R.K. Stanley *et al.* (2023) found that *Fraxinus pennsylvanica* marshall trees are resistant to the emerald ash borer. However, many years are needed to support this trait in the offspring. J. Meger *et al.* (2024) in Poland, using six significant single nucleotide polymorphism loci, proposed 300 *F. excelsior* trees from 30 populations for future breeding

programmes to control ash dieback. J. Rozsypálek *et al.* (2023) injected ash trees infected with *H. fraxineus* with fungicides and observed a complete cessation of necrosis growth during the first three months after injection. However, until these programmes are implemented, monitoring remains the most effective control measure, along with continued sanitary felling of infested or infected trees. Regular inspections help to identify early signs of damage, allowing timely intervention. In addition, the removal of affected trees prevents the spread of pests and diseases to healthy parts of the forest.

Conclusions

According to the health condition index, the inspected ash stands are weakened and their health deteriorates with age. The health condition of ash is the worst in the shelterbelts, in the damp relatively fertile forest site conditions (C₄), in the stands of vegetative origin, with a lower relative stocking density and in the stands with *Alnus glutinosa* as the main forest forming species. Dry branches are the most frequent symptom of ash tree damage (over 80% of trees). This symptom is most frequent in the shelterbelts, in the damp relatively fertile forest site conditions (C₄), in the stands of vegetative origin, with a lower relative stocking density and older than 60 years.

The prevalence and severity of epicormic shoots were the highest in the forest shelterbelts, in damp relatively fertile forest site conditions (C₄), and in the stands of vegetative origin. These indicators increased with tree age and decreased with the relative stocking density. Collar rot was the most frequent and severe symptom of ash damage in the forest shelterbelts, in the stands of vegetative origin, in the damp relatively fertile forest site conditions (C₄), and in the stands with *Alnus glutinosa* as the main forest forming species. The severity

of collar rot increased at the relative stocking density of 0.8. The highest prevalence and severity of bark beetle infestation were found in the forest shelter belts and, in the damp, relatively fertile forest site conditions.

The data obtained indicate the need to grow ash of seed origin in mixed stands with oak. In view of the spread of native and alien ash pests, it is necessary to monitor the health

of the trees in order to detect pathological processes in good time and to remove infected or infested trees immediately.

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Conflict of Interest

None.

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Симптоми пошкодження *Fraxinus excelsior* у Житомирському Поліссі

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Анотація. Вивчення ясеня звичайного (*Fraxinus excelsior* L.) є важливим через його погіршений санітарний стан, який спричинений зміною клімату, антропогенним навантаженням, хворобами та пошкодженнями фітофагів, що залежать від локальних умов і типу насаджень. Метою дослідження було визначити лісорослинні умови та інші характеристики насаджень, які найбільшою мірою сприятливі для поширення та розвитку симптомів ослаблення ясеня у Житомирському Поліссі. Дослідження проведено на прикладі філії «Звягельське лісове господарство». Оцінено санітарний стан дерев ясеня звичайного, симптомів їхнього ослаблення та залежності їхніх поширення та інтенсивності від категорії лісів, типу лісорослинних умов, головної лісоутворювальної породи, походження дерев ясеня, віку та відносної повноти насаджень. Більшість обстежених насаджень виявилися ослабленими. Встановлено, що санітарний стан *F. excelsior* погіршується з віком. Він є найгіршим у лісових смугах, у сирому сугруді (C₄), у насадженнях вегетативного походження, з найменшою відносною повнотою та з *Alnus glutinosa* як головною лісоутворювальною породою. Найбільш поширені симптоми ослаблення ясеня – сухі гілки, водяні пагони, окоренкові гнилі та поселення ясеневих лубодідів. Поширеність та інтенсивність більшості симптомів біли

найвищими у лісових смугах, сирому сугруді (C₄), у насадженнях вегетативного походження, з відотною повнотою 0,6 і віком понад 60 років. Інтенсивність розвитку окоренкових гнилей була більшою за відотної повноти 0,8. Рекомендовано вирощувати *F. excelsior* у мішаних насадженнях, переважно разом із *Quercus robur* і надавати перевагу насінневному походженню. Зазначено, що для вчасної ідентифікації патологічних процесів та відбору дерев у вибірковій санітарній рубці необхідно здійснювати моніторинг санітарного стану дерев *F. excelsior*. Результати дослідження можна враховувати для виявлення осередків шкідників і збудників хвороб і запобігання ослабленню й загибелі лісів

Ключові слова: санітарний стан дерев; сухі гілки; водяні пагони; окоренкові гнилі, короїди; поширення симптомів; інтенсивність розвитку симптомів

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Regarding the issue of growing Scots Pine forests in Polissya

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Abstract. Issues related to forest growth are essential in the forest management system. Reforestation, forest care, logging, and other activities require continuous improvement and new approaches to planning and implementation over time. This should be done in compliance with the principles of sustainable, continuous, and rational use of forest resources. Therefore, the study aimed to analyse scientifically based approaches to forest restoration, thinning, and principal felling and suggest optimal methods for growing Scots pine forests in Polissya. It was analysed scientific research, compared experimental data on different methods of Scots pine growing, and critically assessed the “Rules for Principal Felling” requirements for conducting Shelterwood cutting in Scots pine forests. On one- and three-year-old fell areas of Polissya, the optimal natural regeneration of Scots pine is observed in a wet subir, minimal – in a fresh bir, and average - in a fresh subir and a wet bir. On a one-year-old Scots pine fell area, dense natural regeneration is observed up to 50 m from the neighbouring forest. It becomes medium at 51-100 m and rare beyond 100 m. The maximum stocking (420-436 m³ per hectare) and optimal stand structure at 51 years can be achieved through linear thinning. Creating Scots pine forests in a fresh subir with Common oak is irrational, as oak cannot survive in the stand. Deciduous species, such as Common oak, appear naturally in such areas after 30 years and can form a second layer in the stand. The use of nature-saving technologies for clear-cutting allows for the preservation of undergrowth. The last round of shelterwood cuttings in pine forests with viable undergrowth of more than 8,000 units per hectare should not be scheduled in 4-7 years, as required by the “Rules

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for Principal Felling”. The study results can be used to improve regulatory documents and offer practical recommendations for the rational growing of Scots pine forests in Polissya

Keywords: natural forest regeneration; Scots pine; care cuttings; forest stand; principal felling

Introduction

The issue of growing Scots Pine forests in Polissya is essential to ensure their sustainable development and biodiversity conservation. The sustainable development and biodiversity conservation of pine forests are crucial, allowing forestry specialists to optimize forestry practices according to regional environmental and climatic conditions. The growing of Scots pine forests in Polissya presents specific challenges due to the region’s soil and climate conditions, necessitating a holistic approach considering environmental, forestry, and economic factors and implementing suitable forestry practices. The research on the biological sustainability of forest stands is a crucial subject studied by scientists in various countries, including Ukraine. This research covers measures to encourage natural regeneration, thinning techniques and technology, and the implementation of continuous cover forestry.

In a study by J. Brichta *et al.* (2020), the authors researched how stand density and soil preparation methods affect the natural regeneration of pine forests. The research revealed that for the regeneration of Scots pine, reducing stand density to 0.4 during gradual felling is optimal, as it creates better conditions for germination and has a positive effect on the soil. Furthermore, the treatment with a forestry routing cutter was the most effective soil preparation method. As an alternative to clear-cutting, the researchers recommend gradual felling with preliminary soil preparation to mitigate the adverse effects of climate change.

It is important to note that in addition to the density and age of the stand, other factors

influence the natural regeneration of Scots pine. These factors include grass cover density, forest floor thickness, and microrelief. According to a study by M. Shevchuk *et al.* (2021), the best Scots pine regeneration occurs when the grass cover closure is low (0.1-0.4) or medium (0.5-0.7). The ideal litter thickness for seedlings is 1-3 cm in 68-year-old stands, 3-6 cm in 65, and up to 2 cm in fell areas. The most favourable conditions for undergrowth occur when the litter thickness ranges from 1 to 6 cm, and the terrain is flat. The authors recommend clearing dense understorey 2-3 years before principal felling.

The study conducted by Ukrainian scientists V. Lavnyy *et al.* (2022) found that natural reforestation is most successful in areas with low and sparse grass cover, allowing seedlings to grow without hindrance. In these conditions, there is an increase in seedlings and undergrowth of Scots pine during the growing season. To improve seed germination, researchers recommend soil mineralization, which can lead to an 80% increase in viable self-seeding and undergrowth. It is also important to promptly remove weeds and unwanted vegetation to protect the seedlings.

This principle, as per R. Jandl *et al.* (2019), involves maximizing the natural seed potential of forests to establish biologically sustainable and highly productive forest stands. The authors emphasize that climate change necessitates more adaptive forest management. The uncertainty surrounding the extent of climate change and the response of forests, along with the limited interpretation of climate change

experiments, presents foresters with a wide range of practical options but few clear recommendations for making management decisions on the best ways to manage forests. Consequently, this issue remains relevant and is the focus of research by many scientists.

The study by Y. Nuutinen & J. Miina (2023) examined the effects of corridor thinning on the growth of Scots pine stands aged 20-50 years. The research revealed that trees located 2-3 meters from corridors that are 3-5 meters wide experience higher annual volume growth, particularly in the first 4-5 years after felling. The growth of edge trees compensated for 40% of the losses caused by tree felling in the corridors. The authors emphasize the need for further research to determine the long-term effects and optimal corridor width.

Silvicultural measures for forest care at different ages can be used to manage the impact of environmental factors and maintain sustainable natural or partially natural forests. In a study by F. Huth *et al.* (2022), the natural regeneration of Scots pine was studied, and the authors found that adjusting the density of the upper layer of the forest stand had a significant impact on this process. They observed that reducing the number of trees in the upper layer from 400 to 230 per hectare after thinning had a notable effect on the absolute density of natural regeneration. The measures have a more significant impact on the growth and development of seedlings. A higher tree layer density, specifically more than 300 trees per hectare, leads to a high initial natural regeneration density. However, after five years, it leads to significant losses in growth and a decrease in viability. A lower stand density of 200-300 trees per hectare ensures better growth of natural regeneration but requires more maintenance. There's a risk of seedling suppression by ground vegetation. Therefore, adjusting the upper stand layer density can be

an effective silvicultural measure in establishing sustainable natural forests dominated by Scots pine.

In summary, it is significant to note that natural pine forests demonstrate higher resistance to various natural factors, including climate change. As per W. Beese *et al.* (2019), these forests are well adapted to specific soil conditions, which helps their sustainability and productivity as they mature. As noted by J. Miettinen *et al.* (2024), given the significant advantages of natural forests over forests of artificial origin, promoting the emergence of natural regeneration and its preservation in some cases remains a complex and unsolved forestry task, as the success of such measures depends on several factors (environmental and weather conditions, silvicultural stand indicators, frequency of seed production of the parent stands, and biological characteristics of the tree species). Therefore, one of the most relevant areas of forestry research is the study of interdependencies between environmental factors, forest management, and the processes of growth and development of forest ecosystems in the context of the formation of biologically sustainable, time-continuous, and productive stands in the face of climate changes.

The study aimed to scientifically explore approaches to forest regeneration, thinning, and principal felling and to recommend the most effective methods for growing Scots pine forests in Polissya.

Materials and Methods

The research was conducted using the method of analysis. The research focused on studying the natural Scots pine regeneration processes and the methods for growing pine forests in Polissya. The references and relevant aspects analysed in this study were summarized in Table 1.

Table 1. Information sources and aspects studied

References	Aspects analysed
M. Gordienko & N. Gordienko (2005), V. Levchenko (2007), M. Gordienko <i>et al.</i> (2007), A. Vyshnevsky (2010), S. Drobush & V. Levchenko (2011), V. Borodavka & O. Borodavka (2022)	Natural Scots pine regeneration in various types of bir and subir forests (fresh bir (A_2), wet bir (A_3), fresh subir (B_2), wet subir (B_3), fresh sugrud (C_2)), beneath the canopy of various types of Scots pine stands: high- (0.8 and above), medium- (0.6-0.8) and low-density (0.4-0.5); the regeneration also occurs in clearcut areas of different ages in the Ukrainian Polissya.
P. Brang <i>et al.</i> (2018), R. Jandl <i>et al.</i> (2019), V. Lavnyy <i>et al.</i> (2022), A. Zawadzka & A. Slupska (2022), J. Miettinen <i>et al.</i> (2024)	Growing Scots pine forests

Source: developed by the authors

Using the description method, it was presented experimental studies by V. Svyrydenko *et al.* (2006) from the paper "Growth and productivity of artificially created Scots pine forest in fresh subsoil conditions depending on the method and regimes of silvicultural care". The growing of single-species Scots pine stands of artificial origin in the conditions of fresh subir (B_2) in Plesetske (Dzvinkivske) forestry of the Boyarka Forest Research Station (FRS) was carried out in six experimental sections (A, B, C, D, E, F) measuring 40×50 m (area 0.2 ha) each. The Scots pine stand was established by mechanized planting of single-species Scots pine forest on a completely uprooted clearcut area, with planting sites placed 1.5 m width between rows and 0.75 m distance in rows. Section A controlled other sections (B, C, D, E, F), and only dead trees during the stand's life were cut down in this section. Buffer zones 5.0 m wide between the sections on all sides were arranged. From the age of 11, pre-commercial thinning was carried out in section B at a low intensity (up to 15% of the stand's stock), maintaining a stand density of 0.9; in section C, high intensity (26-35% of the stand's stock) was applied, maintaining a stand density of 0.7; in section D, an average intensity (16-25% of the stand's stock) was used, maintaining a stand density of 0.8.

Pre-commercial thinning was carried out manually in the A, B, C, and D sections using a selective method. In section D, thinning was done using a linear method at 11 years, with every second row of trees being cut down and the row spacing doubled from 1.5 to 3.0 meters. In section E, the thinning was carried out in two stages: at 11 years, every fourth row of trees was cut down, and at 15 years, every second row was cut down. The felled trees in sections D and E were bundled and skidded by tractor to an upper storage area. The comparison method matched Scots pine stands' silvicultural and taxation parameters grown under various regimes and thinning methods. Attention was also given to comparing Scots pine stand stocks and the formation of the spatial and parametric structure in the six sections (A, B, C, D, E) at the age of the first thinning (25 years) and late thinning (51 years).

The paper used the analogy method to describe the creation and development of forest stands in the fresh subir (B_2) conditions of Polissya, which should match the characteristics of natural stands in specific forest vegetation conditions. It highlights the importance of growing long-lived, highly productive, and biologically resistant forest stands, considering natural changes and growth processes. Forest management should focus on growing

native forest stands consisting of tree species that best adapt to the forest and vegetation conditions.

The authors used critical evaluation to analyse the requirements of the Rules for Principal Felling (Order of the State..., 2009) for the thinning cycle and the amount of natural regeneration of economically valuable tree species of seed origin up to 0.5 m in height during shelterwood cutting in Scots pine forests. They also paid attention to growth inhibition (such as insignificant height growth, pale green needles, and shortened, medium, or low density) and loss of viability with the age of natural regeneration of Scots pine without sufficient light beneath the canopy of parent stands.

The analysis focused on clear-cutting technology for principal felling, clearing areas from slash, tree felling, and skidding directions. It also promoted employee awareness to maximize preserving natural forest regeneration.

Results and Discussion

Natural forest seed regeneration is an essential mechanism for long-term sustainability and biodiversity for forest ecosystems. It can be an influential factor in maintaining the forest's genetic diversity, as the new generation of trees comes from the seeds of different parent trees. This process also allows forests to adapt to changing environmental conditions and maintain ecological balance. Forest ecosystems can regenerate through natural regeneration and maintain productivity and stability without significant human disturbances. Natural forest seed regeneration occurs in four stages: 1) tree seed-bearing, 2) seed germination and seedling formation, 3) seedling growth and development, and 4) growth and development of the undergrowth. The process concludes with the closure of the young forest generation. Table 2 illustrates suitable and unsuitable conditions for natural forest seed regeneration.

Table 2. Conditions for natural forest seed regeneration in clear-cut areas

Suitable	Unsuitable
Maximum light supply	There is a risk of damage to the young forest generation from frost and high air temperatures
Absence of root competition from the parent trees	Drying of the surface soil layer
Intensive forest floor decomposition and its disappearance	Soil compaction by sedge and cereal grass species and growth of tree vegetation
The positive impact of certain grass species (<i>Chamaenerion angustifolium</i> (L.) Scop., <i>Calluna vulgaris</i> (L.) Hill.)	

Source: developed by the authors based on A. Shvidenko & B. Ostapenko (2001)

A rapid change in the growth and development conditions in clear-cut areas often leads to the forest regeneration that appears beneath the forest canopy, once in the open space, cannot withstand the change in living conditions and usually dies. After cutting down the parent stand, the growth of light-loving Scots pine adapts to the new conditions relatively quickly compared to shade-tolerant tree species. The more rapidly the light regime and soil moisture

conditions change after the stand is cut down (causing changes in photosynthesis, transpiration, metabolism, etc.), the worse, the younger generation of the forest tolerates them and the faster it dies.

The success of natural seed regeneration largely depends on the conditions of the forest. The regeneration of a particular plant improves with increasing soil moisture and fertility. For instance, different types of forest vegetation

conditions (FVC) affect the natural Scots pine regeneration. The optimal FVC sequence for regeneration is as follows: wet subir (B_3) → fresh subir (B_2) → wet bir (A_3) → fresh bir (A_2) (Drobush & Levchenko, 2011).

The amount of natural forest regeneration is directly influenced by soil moisture. Specifically, beneath the canopy of Scots pine stands in fresh subir (B_2), there were 0.3 to 0.7 thousand seedlings per hectare. In the transition from fresh to wet subir (B_{2-3}), the amount of natural forest regeneration ranged from 0.2 to 4.8 thousand seedlings per hectare, and in wet subir (B_3), it ranged from 0.6 to 12.4 thousand seedlings per hectare. The most common natural Scots pine regeneration was observed under parent stands with a density of 0.6–0.8. Deviations from this density, either higher or lower, decreased seedling emergence and undergrowth preservation. In high-density stands (0.8 and above),

this is due to the lack of light for natural pine regeneration and a forest floor depth. In low-density stands (0.4–0.5), it is due to the intensive growth of herbaceous plants (Gordienko *et al.*, 2007).

Thus, natural Scots pine regeneration should be used, considering suitable (seed availability; less physical evaporation of moisture from the surface soil layers; reduced temperature fluctuations; absence or slight soil compaction by sedge and cereal vegetation) and unsuitable (insufficient light; root competition from parent trees; depth of forest floor) conditions beneath the forest canopy and the effect of positive and negative factors on the clear-cut areas. Dense natural Scots pine regeneration (exceeding 8 thousand pcs. per ha) on a one-year-old clear-cut area typically forms around 50 m from the uncut part of the parent pine stand, particularly from the prevailing westerly winds (Fig. 1).

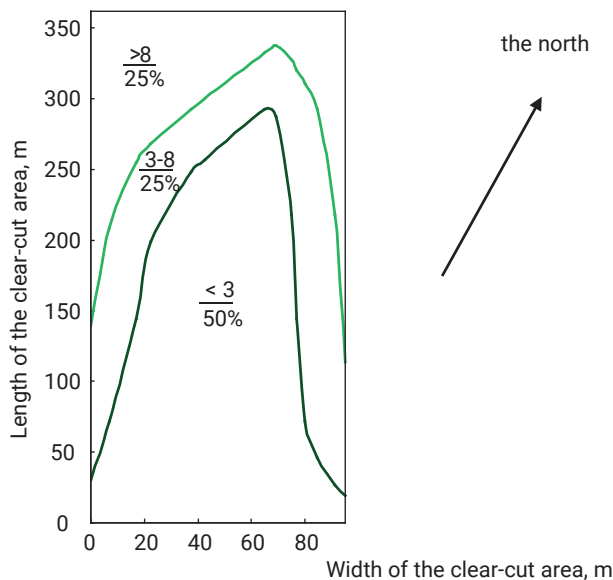


Figure 1. Distribution of natural Scots pine regeneration in fresh subir (B_2) on a one-year-old clear-cut area of Dzvinkivske forestry in Boyarka FRS

Note: numerator – thousand pcs. per ha, denominator – percentage of the covered area

Source: V. Levchenko (2007)

Further west to east is a zone of medium natural Scots pine regeneration 51-100 meters away and a zone of rare natural regeneration at 101 meters or more. The dense and medium regeneration zone covers about 25% of the clear-cut area, while the rare regeneration zone covers about 50%. These details are essential when planning measures to promote regeneration (Levchenko, 2007).

Research by V. Borodavka & O. Borodavka (2022) revealed that in the logging blocks of Western Polissia, after carrying out narrow strip clear-cuts (up to 50 m in width) in wet subir (B₃) forest type, there were between 8.4 and 17.3 thousand natural Scots pine regenerations per hectare. Furthermore, the undergrowth distribution was uniform, and the average share of viable natural regeneration was 78%. In forest areas, after clearcutting, the recovery of vegetation cover is slow, with herbaceous species dominating in the initial stages of succession. The total recovery of the forest ecosystem can take decades or even centuries, depending on factors such as soil compaction, climate, and the availability of seed sources (Buma & Wessman, 2011). However, a study by H.D. Reátegui *et al.* (2021) on the impact of partial stand retention during clearcutting on natural regeneration processes in Swedish boreal forests found that this approach promotes a higher diversity of valuable tree species, their composition, and structure compared to traditional clearcutting methods. Thus, because of clear-cutting, a sharp change in environmental factors is observed in a forested area that was covered with forest, leading to the disappearance of the forest environment

that had been formed over decades. According to V. Lavnyy *et al.* (2022), rapid changes like these cause a significant reduction in the diversity of soil organisms, including invertebrates, fungi, and bacteria, which negatively impacts the decomposition of organic matter, biological nutrient cycling and soil humus formation. It is important to note that the growth of seedlings or self-seeding of previous natural regeneration in areas where clear-cutting has occurred is hindered, leading to subsequent drying out.

The process of forest regeneration concludes with the crowns of the young stands closing. Later, when crowns are deeply intergrown in single-species young stands and minor species in mixed stands threaten the main species, thinning should be initiated to create the optimal growth and development conditions for the preferred trees.

Thinning operations in young pine stands are conducted manually using a selective method. Consequently, there is a need for more workers in sparsely populated areas of Ukraine, resulting in delays in these operations. This problem is solved through linear thinning in young stands of artificially grown pine. Research by V. Svyrydenko *et al.* (2006) studied the impact of thinning in different methods and under various rarefaction regimes in single-species Scots pine forests of artificial origin. The study found that after the first thinning at the age of 25, the most extensive stand stock (344 m³ ha) was observed in the control group (section A), where no thinning was carried out, and the stand was formed by the natural rarefaction process (Table 3).

Table 3. Taxonomic forest stands parameters in sections of the permanent plot in block 27 of Dzvinkivske forestry, Boyarka FRS, after thinning at 25 years

Sections	Stand composition	Stand density	Average		Stand stock, m ³ /ha
			height (H), m	DBH, cm	
A	100% Scots pine	1.00	15.6	13.0	344
B	100% Scots pine	0.73	17.0	16.0	260

Table 3, Continued

Sections	Stand composition	Stand density	Average		Stand stock, m ³ /ha
			height (H), m	DBH, cm	
C	100% Scots pine	0.79	16.5	15.4	287
D	100% Scots pine	0.72	16.8	15.8	253
E	100% Scots pine	0.70	16.7	15.7	254
F	100% Scots pine	0.70	16.0	14.9	252

Source: V. Svyrydenko *et al.* (2006)

The stands' stock in section D was 254 m³/ha, where every second row of trees was cut through linear thinning at 11 years of age. In section E, the stock level was 252 m³/ha. Here, every fourth row of trees was cut through linear thinning at 11 years of age, and every second row was cut at 15. In sections B, C, and D, where thinning was carried out manually with different intensities (weak in section B, strong in section C, and medium in section D) in a selective manner, the stock

level after thinning was higher compared to sections D and E, where linear thinning was carried out. After thinning, lower stands' stock was observed in sections B, C, and D (380-406 m³/ha), and the highest stock levels were found in sections D (436 m³/ha) and E (420 m³/ha), where thinning was carried out using a linear method. This contributed to forming a more optimal spatial and parametric structure of the stands compared to sections B, C, and D (Table 4).

Table 4. Taxonomic forest stands parameters in sections of the permanent plot in block 286 (27) of Plesetske (Dzvinkivske) forestry, Boyarka FRS, after thinning at 51 years

Sections	Stand composition	Stand density	Average		Stand stock, m ³ /ha
			height (H), m	DBH, cm	
A	100% Scots pine	0.69	25.5	25.5	413
B	100% Scots pine	0.68	25.6	25.5	406
C	100% Scots pine	0.67	25.5	25.8	398
D	100% Scots pine	0.63	26.4	25.8	380
E	100% Scots pine	0.73	25.8	25.5	436
F	100% Scots pine	0.67	26.7	25.5	420

Source: developed by the authors

In single-species Scots pine young stands with row spacing of 1.5-2.0 m, growing in fresh subir (B₂), thinning can be omitted. It is recommended to begin treatment at the age of 11-13 years, thinning in a linear method by cutting down every 4th row of trees. As the tree canopy closes after cutting down the rows in the third year, it is advisable to carry out the treatment at the age of 14-16 years by cutting down the trees of the middle row in three-row strips. When

cutting rows, the trees' crowns grow towards the free space, so selective sampling of trees in the rows should not be delayed for up to 20 years. Timely selection of trees makes it possible to form symmetrical crowns with respect to the trunks, ensuring stand growth without the need for thinning for up to 25 years.

Linear thinning by cutting down every second row of trees at 11-13 years is impractical. This method disrupts the stand canopy and

causes a sharp change in the microclimate, leading to soil compaction. Linear thinning is suitable for Scots pine, which stands up to 20 years old and is technologically simpler than selective cutting. It is recommended that linear thinning from the main skidding road be commenced by cutting down trees with a chainsaw. Increasing the distance between rows of trees allows the use of technological corridors for skidding the logged trees with small tractors equipped with hydraulic grippers to the upper storage area.

Forest stands should grow using native tree species best suited to the specific forest conditions. However, sometimes, foresters introduce native tree species into artificial forests without considering their bioecological properties. In such cases, attempts to achieve the desired composition and stand layers in the future are futile.

In the fresh subir (B_2) conditions of Ukrainian Polissya, native stands consist mainly of Scots pine in the first layer and Common oak in the second layer. It is inefficient to simultaneously introduce pine and oak rows into these stands, as Scots pine grows faster and overshadows the oak, drying out due to lack of sunlight.

Research by V. Svyrydenko *et al.* (2005) found that in single-species Scots pine stands of artificial origin in fresh subir conditions (B_2), deciduous tree species, such as common oak, naturally start to appear after 30 years of age. This occurs when suitable environmental conditions (light, heat, moisture) are established in the stand to support their average growth and development. The appearance of deciduous species in the forest area is linked to deciduous trees in the nearby top layer of stands.

In a fresh subir (B_2), it is not suitable to establish pine-oak stands and plant oak and pine seedlings simultaneously. In this case, the productivity of a mixed oak-pine stand is lower than that of a single-species Scots pine stand (Svyrydenko *et al.*, 2005).

The dominant forestry practice in Ukraine is clear-cutting. Maintaining natural forest regeneration under the forest canopy relies on equipment, technological processes, organization, and logging operations. Therefore, clear-cutting should be conducted using environmentally friendly technologies to maximize the preservation of economically valuable tree species. Before clear-cut starting, it's essential to mark out skid trails on the logging area, determine the direction and angle of tree felling (up to 40°), designate areas for stacking the felling slash, and plan methods for clearing the logging area while considering the natural regeneration of the forest on the site. It's also crucial to educate employees about the significance of maximizing the preservation of the undergrowth of economically valuable tree species. By using this approach to clear-cutting, it's possible to preserve most of the natural regeneration of the forest in the parent stand.

According to the Rules of Principal Felling (Order of the State..., 2009), shelterwood cutting in Scots pine stands is carried out. The final shelterwood cutting step in pine stands is scheduled for 4-7 years if there is a viable undergrowth of economically valuable tree species of seed origin up to 0.5 m in height and in the amount of at least 8 thousand pcs per hectare evenly distributed over the area. With such a recurrence period in pine stands, in the absence of sidelight, the natural regeneration of Scots pine is usually depressed - resulting in insignificant growth in height, pale green needles, shortened, medium or low density, etc. It is important to have viable Scots pine undergrowth in a stand over 0.5 meters in height. It would not be economically rational to ignore the presence of such undergrowth. Considering the requirements of the Rules (Order of the State..., 2009) for the final step of shelterwood cutting in pine stands and the current state of natural regeneration of Scots pine beneath the

canopy of parent stands, it is considered appropriate that if there are more than 8 thousand viable economically valuable tree species per hectare in pine stands, the final step of shelterwood cutting should be appointed without considering the period of repetition and without dividing the undergrowth by height. Appointment of the final step of shelterwood cuttings in Scots pine stands is advisable only in the absence of natural regeneration or undergrowth of economically valuable tree species in less than 8,000 pieces per hectare within 4-7 years.

In developed countries, there is a growing interest in using non-clearcutting methods and close-to-nature forestry, which involves organizational and forestry measures to restore and establish sustainable, multi-age, complex stands of natural and combined origin. This interest is driven by modern advances in science and technology and a deep study of forest ecology and ecosystem formation processes. In the research by A. Zhezhkun *et al.* (2023), the authors studied the effectiveness of non-clearcut methods and their impact on the natural regeneration of Scots pine forests. The study found that after the initial step of shelterwood cutting in mature pine stands, which reduced the stand density to 0.3-0.4 for 4-5 years, the density of pine undergrowth was 8-20 thousand per hectare, evenly distributed across the site. The preservation of the undergrowth after the initial cutting was between 71-96. At the age of 5-7 years, the formation of mixed pine stands of different ages was noted. It was also observed that 11 years after the second step of shelterwood cutting, mixed pine stands resulting from natural and combined forest regeneration methods had formed. Therefore, the authors suggest that using non-clearcutting systems is advisable to establish sustainable and complex forests through close-to-nature silviculture and sustainable forest management, ensuring the continuity of forest cover.

L. O'Brien *et al.* (2021) also share this opinion, noting that non-clearcutting methods are closer to the forest's nature, aimed at preserving biodiversity, stand structure, forest soil, and forest ecosystem functions than traditional clearcutting, and have significant advantages. Therefore, it is advisable to carry out harvesting in ways and technologies that will maximise the preservation and restoration of the forest's nature.

Researchers and forestry practitioners face a particular challenge in studying how various silvicultural measures and technologies impact the growth and development of forest stands. In the paper by N. Saarinen *et al.* (2020) scientists investigated how different levels of thinning in 45-70-year-old stands affected the growth of individual Scot's pine trees. The study involved sampling trees for cutting using bottom, top, and combined methods. The authors found that the most significant increase in trunk diameter at a height of 1.3 meters and trunk volume occurred with thinning at an intensity of over 35% using the bottom method. The highest tree height growth was observed in the control plots without silvicultural measures. This indicator increases significantly with a decrease in thinning intensity. Similar results were obtained by E. Valinger *et al.* (2018). Their study indicates that different thinning methods and intensities can significantly affect Scots pine's height, diameter, and stock due to changes in light, temperature conditions, and soil moisture. This is important for practical silviculture, as it allows one to choose optimal thinning strategies based on forest growing objectives – whether to maximize stock, obtain trunks of a particular shape, or promote natural regeneration. Additionally, the results demonstrate that the impact of thinning can vary depending on forest conditions, highlighting the importance of considering typological features when planning forest management measures.

The natural regeneration of Scots pine forests is crucial for maintaining biodiversity and ecological balance in forest ecosystems. According to A. Felton *et al.* (2020), naturally regenerated pine forests have a more complex structure, contributing to more resilient forest ecosystems with higher biodiversity. After silvicultural measures are taken to enhance the natural regeneration process, the stand is characterized by favourable ecological conditions for the emergence of economically valuable tree species. The authors emphasize that natural Scots pine forests are more resilient to climate change, have a higher capacity to sequester carbon, and are better adapted to specific forest conditions, ensuring their stability and productivity until maturity. According to D. Simon & A. Ameztegui (2023), the study also underscores the significant impact of thinning on the provision of ecosystem services in Scots pine forests. These findings highlight the necessity of adaptive forest management, considering various forestry objectives and future climate change, to ensure sustainable forest management and preserve forest ecosystem functions.

J. Dlugosiewicz *et al.* (2019) found that the success of natural forest regeneration is significantly influenced by soil fertility and moisture content. The authors studied the effectiveness of natural and artificial Scots pine regeneration in different forest types. They emphasized that the restoration method significantly affects forest growth parameters and silvicultural and economic indicators, especially in fresh, moist conditions. Forest stands established through artificial regeneration exhibit better growth rates in the first few years than those naturally regenerated. However, after 5-6 years, naturally regenerated stands catch up and show higher viability and resistance to harmful insects and forest diseases. The paper also notes that in contrast to young forest stands, areas with natural regeneration require intensive

silvicultural treatments with shorter intervals. Scientists point out that forests of natural origin are characterised by high biological stability and are genetically and ecologically better suited to specific forest conditions. This is a fundamental silvicultural argument, given the current climate instability and its impact on forest phytocoenoses. Therefore, foresters can consider these features and implement approaches of close-to-nature silviculture in their forest management practices.

A study by A. Zawadzka & A. Slupska (2022) found that the natural regeneration of Scots pine beneath forest canopy enhances the resilience and viability of forest ecosystems. This conclusion was drawn after observing the natural regeneration of Scots pine beneath the canopy of a sparse forest following hurricane winds. The researchers' main goal was to improve current forestry practices and develop methods for establishing diverse stands through natural regeneration. The authors highlight that more than 65% of the studied Scots pine seedlings are of high or good quality and are viable. The most significant reforestation was found in plantations >40 years old, with a density of 0.5-0.6. Thus, the researchers recommend that natural forest regeneration be considered to restructure pine monocultures, increasing their resilience to negative natural factors. This approach is presented as an alternative method of restoring pine forests in areas exposed to strong winds.

When growing forests, it's essential to consider the physical and geographical conditions, forest vegetation, tree species' bio-ecological properties, the forest stands' paleo-climate, and human activity. Natural forest regeneration should be fully implemented in areas with favourable forest conditions. Further formation of forest stands by pre-commercial thinning should be carried out using rational growing regimes and cutting methods

based on forest-typological knowledge of native stands in specific forest types. The technology and process of harvesting should be determined based on the presence or absence of undergrowth of economically valuable tree species on the forest plot.

Conclusions

The analysis of scientifically based approaches to forest regeneration, formation, thinning, and principal felling forms the basis for implementing optimal methods for growing Scots pine forests in Polissya. The primary focus is maximizing Scots pine's natural regeneration, particularly in wet subir conditions (B_3), where this process is most effective. It is crucial for forest areas where clear-cutting occurs up to 50 meters from the edge of the uncut part of the forest due to prevailing winds, contributing to Scots pine's dense natural regeneration.

In artificially created young Scots pine stands characterized by high productivity and row spacing of 1.5-2.0 m, pre-commercial thinning is recommended using a linear method. This method has an advantage due to its better silvicultural impact on the stand and contributes to forming the optimal spatial and parametric stand structure. The linear method of thinning allows for mechanizing the process of skidding felled trees, which is especially significant in sparsely populated

areas where the issue of attracting labour can be problematic.

In the fresh subir (B_2) of Ukrainian Polissya, the optimal approach to forest regeneration is to create single-species Scots pine stands. Once the stand is 30 years old, thinning should be carried out, considering the presence of native species, such as Common oak and others. These species can form a second layer in the future, enhancing the sustainability and ecological value of the forest stands.

Harvesting should prioritize environmentally friendly technologies that ensure the preservation of natural regeneration, especially of the main species, such as Scots pine. The final step of shelterwood cutting in Scots pine forests should be carried out only if there is a viable stand of economically valuable tree species, with at least 8,000 trees per hectare, without differentiation by height. This approach ensures sustainable forest development and preserves its economic and environmental value.

Further research will involve an in-depth analysis and synthesis of new research results on the growing of Scots pine forests in Polissya.

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Conflict of Interest

None.

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До питання вирощування соснових лісів Полісся

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Анотація. Питання, пов'язані з вирощуванням лісів, є актуальними в системі ведення лісового господарства, оскільки лісопоновлення, догляд за лісом, рубки та інші заходи з часом потребують удосконалення та нових підходів до їх планування і виконання з дотриманням принципів невиснажливого, безперервного і раціонального використання лісових ресурсів. Тому метою дослідження було проаналізувати науково обґрунтовані підходи до відновлення лісів, здійснення рубок догляду, рубок головного користування та запропонувати оптимальні шляхи вирощування соснових лісів Полісся. Представлено аналіз наукових досліджень, порівняння експериментальних даних вирощування соснових насаджень різними способами, надано критичну оцінку вимогам «Правил рубок головного користування» до проведення рівномірно-поступових рубок у соснових лісах. Встановлено, що на одно- і трирічних зрубках Полісся оптимальне природне поновлення сосни спостерігається у вологому суборі, мінімальне – у свіжому бору, а середнє – у свіжому суборі та вологому бору. Густе поновлення сосни на однорічних зрубках відзначається до 50 м, середнє – на відстані 51-100 м, рідке – більше 100 м від незрубаного лісу. Максимальні запаси (420-436 м³/га) та оптимальна структура деревостанів у віці 51 року досягаються після лінійних рубок прочищення. Створення лісових культур сосни у свіжому суборі з дубом є нераціональним, оскільки дуб випадає з насадження. Листяні види, зокрема дуб, з'являються природним шляхом після 30 років і можуть сформувати другий ярус. Природозберігаючі технології суцільнолісосічних рубок головного користування зберігають підріст. Останній прийом рівномірно-поступових рубок у соснових лісах з життєздатним підростом понад 8 тис. шт./га не варто призначати через 4-7 років, як вимагають «Правила рубок головного користування». Результати дослідження можуть стати основою для вдосконалення нормативно-правових документів та практичних рекомендацій щодо раціонального вирощування соснових лісів Полісся

Ключові слова: природне поновлення лісу; сосна звичайна; рубки догляду; деревостан; рубки головного користування

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Pheromone monitoring of xylophage insects of *Picea abies* (L.) Karst.

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Abstract. Xylophagous insects can inflict significant damage to forests by causing trees to dry out. Pheromone monitoring allows detecting the appearance of these pests in time and taking measures

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to control them. The purpose of the study was to determine the sanitary state of spruce stands and pheromone monitoring of xylophage insect populations. The degree of damage to the spruce plantation was determined in accordance with the scale of sanitary state indices as a weighted average value of the assessment of the distribution of trees of different categories of condition. Based on the results of accounting on the test areas, the sanitary state index (average category) of the spruce stand was calculated, it was found that the most vulnerable to pathological factors were trees in the smallest (8, 12, and 16 cm, respectively) and the largest (44 cm) diameter class. The use of pheromone monitoring to assess the state of forest stands was aimed at identifying the presence of harmful organisms in a certain territory, determining their species composition, abundance, and development dynamics. In the forest area where the pheromone survey was carried out, insects were found and identified, including the sharp-dentated bark beetle *Ips acuminatus*, European spruce bark beetle *Ips typographus*, spruce wood engraver *Pityogenes chalcographus*, synanthropic species of depressed flour beetle *Palorus depressus*, and the predatory ant beetle *Thanasimus formicarius*. The largest number of individuals in traps was recorded in the European spruce bark beetle during the entire observation period, where from 10 to 15 individuals were caught for each trap, as well as in a synanthropic species *Palorus depressus*. The potential reproduction opportunities of xylophage insect populations were analysed, and the population of *Ips typographus* has the highest settlement density, the number of beetles of the younger generation or the production of stem pests of which averaged 34 holes per 1 dm². Despite the low density of the settlement, *Pityogenes chalcographus* has the ability to attack almost healthy trees and forms continuous mass populations in the surveyed plantings together with the European spruce bark beetle. The results obtained will be useful for monitoring and controlling pests, which will allow timely detection and assessment of the level of threat to forest stands

Keywords: phytophagous insects; accounting; pheromone traps; *Ips typographus*; *Pityogenes chalcographus*

Introduction

Forest ecosystems play a key role in the ecological evolution of the biosphere and maintaining its natural state, especially in the modern technological period, when the balance of oxygen and carbon is disturbed under the influence of anthropogenic factors. The composition of forests is undergoing changes, the age structure of forests is changing, the stability and viability of spruce forests are sharply reduced, and their mass death occurs. The area of forest landscapes continues to decline catastrophically, and researchers emphasize that the natural process of forest ecosystem development ensures the stability of mixed forest

stands and their viability, and high productivity of spruce forests under appropriate plant growth conditions.

According to O. Jakoby et al. (2019), spruce stands, especially monocultures, are in a state of degradation and mass drying out. There are several main reasons for the degradation of spruce crops, including, in particular, a decrease in diversity and increased vulnerability to pathogens and pests, disruption of the vital activity of not only the ground part, but also root systems. A decrease in growth and a massive increase in spruce monoculture prevails in mature forests, although smaller volumes are

also observed in middle-aged ones, and even less often in young stands.

P. Lehmann *et al.* (2020) investigated that the European spruce (*Picea abies* (L.) Karst.) has a significant potential for forest restoration, is easily grown in nurseries, successfully takes root in cutting areas, and grows quickly, and its wood is valuable on the market. However, there are certain negative aspects in its genetic structure, such as low wind resistance, vulnerability to rotting diseases of the root system, attacks of phytophagous insects, etc. This is confirmed by the increase in the number of wind trees and the breaking off of spruce branches due to the influence of climatic abiotic factors on spruce stands, and the drying up of plantings due to the intensive spread of pathogens and a complex of insects-phytophagous, which was considered in the study by T. Hlasny *et al.* (2023). It should also be noted that for a significant time of the last century in monodominant spruce plantations in Ukraine, there was a decrease in growth, dryness, and mass drying of spruce.

As noted by S. Karvemo *et al.* (2023), spruce forests in Europe are experiencing large-scale drying caused by spruce bark beetle (*Ips typographus* L.), natural phenomena, and periods of drought that are becoming more frequent as a result of climate change. S. Berthelot *et al.* (2021) proved that tree diversity creates an environment where favored coniferous species are less accessible to bark beetles. *Ips typographus* is one of the most important species that affect the forest ecosystems of Eurasia, causing massive mortality of the host tree *Picea abies* (Hofmann *et al.*, 2024). Global warming and extreme climate events have caused unprecedented outbreaks of xylophage insects in coniferous forests around the world (Marini *et al.*, 2017), hence, J. Romeiro *et al.* (2023) suggested that an effective forest management strategy should assess the structure and composition of plantings to determine potential damage from bark

beetles. Coniferous tree species weakened by abiotic and biotic factors are susceptible to bark beetle colonization. L. Lehmanski *et al.* (2023) found that a significant proportion of trees with weakened protection create favourable conditions for the accumulation of insect populations, but the mechanisms that encourage the search for nutrient plants by pioneer beetles are still unknown to many species, including *Ips typographus*. Consequently, dendrophilous insects have a significant impact on the productivity and stability of stands, since damage can lead to changes in forest biocenoses and even drying out.

The purpose of the study was to investigate the main factors of drying out of spruce stands with an assessment of the sanitary state and analysis of the species composition of xylophage insects by conducting pheromone monitoring.

Materials and Methods

Object of research – the main factors of drying out of spruce stands under the intense influence of abiotic and biotic factors. The subject of the study – pheromone monitoring of insects – xylophages of spruce stands.

The study was conducted during 2023 in a plantation dominated by *Picea abies* in the forestry part of the green zone forests of the Plesetsk Forestry of the separate subdivision of the National University of Life and Environmental Sciences of Ukraine “Boyarka Forest Research Station”, forest crops of heterogeneous composition, namely 30% of Norway spruce (*Picea abies*) aged 46 years, 20% Norway spruce (*Picea abies*) aged 62 years, 20% Scots pine (*Pinus sylvestris*), 30% European white birch (*Betula pendula*) of natural origin and a slight admixture of European aspen (*Populus tremula*) and common oak (*Quercus robur*), with an uneven forest density of 0.85, growth class 1. To determine the dynamics of pathological processes and the volume of drying, field studies and

information from the database of scientific data of the separate subdivision “Boyarka Forest Research Station” of the National University of Life and Environmental Sciences of Ukraine were used.

Detailed forest pathological surveys in the spruce dieback areas were carried out by laying out temporary trial plots around existing group tree dieback areas, according to generally accepted methods (Goychuk *et al.*, 2012; Methodological guidelines..., 2020; Puzrina *et al.*, 2021) and in accordance with regulatory reference materials (Standard of organizations of Ukraine..., 2007). The state of forest stands was determined by the average sanitary state index of trees (I_s), the health of each tree was determined in accordance with the sanitary rules in the forests of Ukraine (Resolution of the Cabinet of Ministers of Ukraine..., 2016).

The following studies were carried out during the fieldwork on the trial areas:

1. Assessment of sanitary state: sanitary state (I_s) of plantings were calculated using the equation (1):

$$I_s = \frac{\sum k_i \cdot n_i}{N}, \quad (1)$$

where I_s – index of sanitary state of plantings; k_i – tree state category (from I to VI); n_i – number of trees of the corresponding state category; N – total number of trees in the sample.

The degree of damage to plantings with a preference in the composition of Norway spruce was determined in accordance with the scale of values of sanitary state indices as a weighted average value for assessing the distribution of trees of different categories of condition. Based on the results of accounting for test areas, the index (average category) of the sanitary state of the spruce stand was calculated

According to the sanitary state indices, plantings are characterised by the following indicators: 1.0-1.50 – healthy; 1.51-2.50 –

weakened; 2.51-3.50 – severely weakened; 3.51-4.50 – drying; 4.51-6.00 – dry (Methodological guidelines..., 2020; Puzrina *et al.*, 2021).

2. Determination of the entomocomplex of insects-phytophagous: identification and counting of insects-xylophages of Norway spruce were carried out. Insect species, their abundance, and distribution in plantings were determined using pheromone traps. A barrier-type trap with a replaceable glass collector and a dispenser with artificially synthesized pheromone was used for accounting *Ips typographus* (manufacturer – BioChemTech, Ukraine). Phenological observations and detection of bark beetles during pheromone surveillance lasted from the second ten days of April to the first ten days of October (Zavada, 2017; Levchenko *et al.*, 2023). Barrier traps were used to detect bark beetles of subfamily *Scolytinae*, to catch adult bark beetles, a pheromone dispenser was attached to the trunk of live trees at the border between live and dead branches (Fig. 1).

Pheromone traps were hung at a height of 1.3 to 1.5 m above the ground at a distance of at least 15 m from each other and 20 meters from the wall of the forest and living trees. When hanging traps, temperature conditions and emergence periods of the bark beetle imago of *Ips typographus* were considered (Zavada, 2017; Puzrina *et al.*, 2021). Control of the number of bark beetles in traps was carried out every 7-10 days and ended on October 7. During the inspection, the traps were regularly checked and cleaned, as dead insects can scare away other insects from the population with their scent.

The population indices of insects that inhabited trees in the drying areas were determined by the pallet method on model spruce trees (Methodological guidelines..., 2020; Puzrina *et al.*, 2021). The state of the population and its impact on forest stands help to assess the quantitative characteristics of the

insect population, in particular: the number, prevalence, production of young beetles (the

number of emergence holes) and the density of the settlement.



Figure 1. Pheromone trap “Barrier” and a dispenser with artificially synthesized pheromone of *Ips typographus*

Source: photo by the authors

When studying the settlement density *Ips typographus*, model trees were cleaned of knots, and a 10 cm wide part of the bark was removed from the base to the top. To determine the settlement density by the number of mother galleries per 1 dm² and production of young beetles by

the number of emergence holes per 1 dm² (Table 1, Fig. 2) the method of accounting palettes was used at the settlement sites of each insect species of the bark beetle subfamily *Scolytinae*.

The collected material was analysed in the laboratory conditions (Fig. 3).

Table 1. Criteria for assessing the density of xylophage insects and the number of young generations

Species	Numerator – settlement density, (number of mother galleries); denominator – the number of the younger generation (emergence holes), units-dm ⁻²		
	low	average	high
<i>Ips typographus</i>	2.5 or less	2.6-6.0	6.1 or more
	10.0 or less	10.1-15.0	15.1 or more
<i>Pityogenes chalcographus</i>	10.0 or less	10.1-20.0	20.1 or more
	20.0 or less	20.1-30.0	30.1 or more
<i>Ips acuminatus</i>	2.0 or less	2.1-5.0	5.1 or more
	6.0 or less	6.1-10.0	10.1 or more

Source: Methodological guidelines for monitoring, recording and forecasting the spread of forest pests and diseases for the flat part of Ukraine (2020), N. Puzrina *et al.* (2021)



Figure 2. Bark beetle passages and emergence holes

Source: photo by the authors

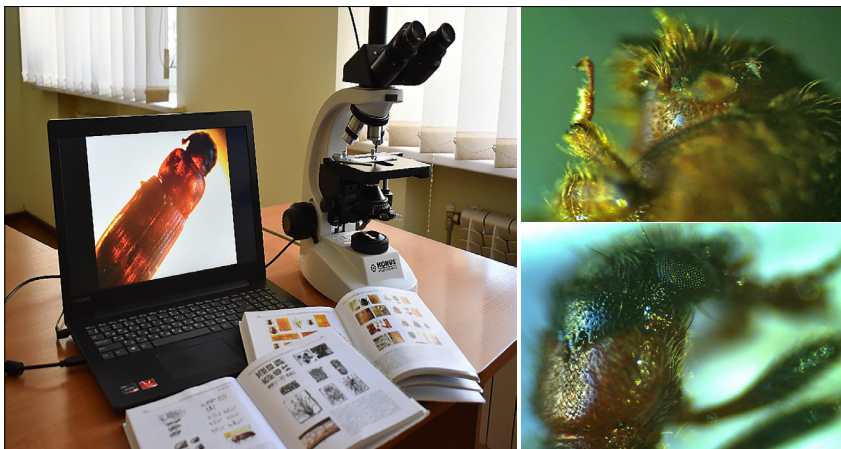


Figure 3. Identification of bark beetles

Source: photo by the authors

The Konus Trinocular Biorex 3 Biological 1,000X microscope was used to identify and photograph captured bark beetles. The authors adhered to the Convention on Biological Diversity (1992) standards and Convention on the Trade in Endangered Species of Wild Fauna and Flora (1973), so experimental studies of plants corresponded to national and international guidelines.

Results and Discussion

The development of drying foci in the study area began with a single death of trees during 2022, but already in 2023 group death prevailed, which tended to expand with the appearance of block and continuous foci over the entire area (Fig. 4). Based on the results of a continuous list of trees of the surveyed plantings on an area of 2.8 hectares, the

sanitary state index of tree species was established. The amplitude of the sanitary state index from 2.43 to 4.05 indicates an almost

uniform nature of weakening and allows identifying a number of factors that cause their weakening (Table 2).



Figure 4. Plantation under study (drying focus)

Source: photo by the authors

Table 2. Sanitary state index

Tree species	Number of trees of the corresponding category, units						Sanitary state index
	I	II	III	IV	V	VI	
<i>Picea abies</i>	9	119	546	398	47	425	IV,05
<i>Pinus sylvestris</i>	29	97	79	36	5	11	II,70
<i>Quercus robur</i>	0	1	7	21	0	0	III,68
<i>Betula pendula</i>	6	29	58	87	0	13	III,46
<i>Populus tremula</i>	2	8	5	0	0	1	II,43
<i>Alnus glutinosa</i>	4	9	48	43	0	3	III,32

Source: compiled by the authors

Assessing the sanitary state of a stand with a composition of 30% Norway spruce (*Picea abies*) aged 46 years, 20% Norway spruce (*Picea abies*) aged 62 years, 20% Scots pine (*Pinus sylvestris*), 30% European white Birch (*Betula pendula*) of natural origin and a slight admixture of European aspen (*Populus tremula*) and common Oak (*Quercus robur*) for the main tree species, it should be noted that the plantings have an average sanitary state index of IV,05 and belong to the drying ones. As can be seen from the analysis of the obtained data from a continuous list of trees of other species,

the *Betula pendula* and *Quercus robur* trees in the plantation are severely weakened.

It was found that trees without damage prevailed in the growth of trees with existing pathological signs of weakening and with indicators of wood decomposition. In accordance with the distribution of trees by diameter class, trees of different diameters died in the drying cells. Comparing the distribution of trees by categories of sanitary state in different diameter classes with the average for planting, it can be noted that the most vulnerable were trees in the smallest (8, 12 and

16 cm, respectively) and the largest (44 cm) diameter class (Fig. 5). Notably, trees with a

diameter of 44 cm as part of the plantation were 62 years old.

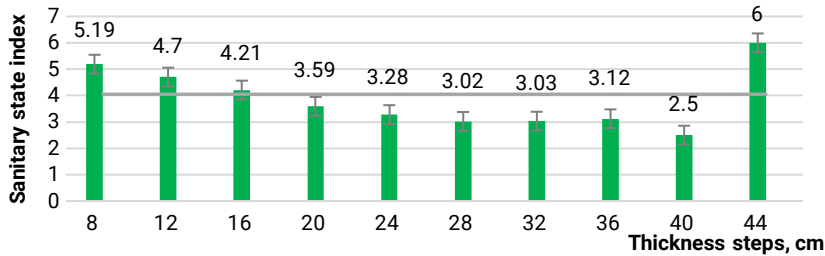


Figure 5. Distribution of *Picea abies* trees of different diameter class

Source: compiled by the authors

In the resulting drying foci, the number of bark beetles was concentrated, followed by the settlement of adjacent spruce trees, the expansion of existing ones and the development of new foci. Spruce trees of different diameter class with a predominance of larger specimens died in the drying foci. In general, during 2022-2023, in plantings with signs of drying out due to the spread of foci of pathological death of trees, the total relative loss in the number of trunks increased, and the condition of very weakened trees worsened to drying out (average index – IV,05). Such dynamics of drying out due to the spread of insect populations-xylophages is inherent in coniferous stands, in particular for pine stands, such dynamics were noted by A.M. Zhezhkun (2021) and N. Puzrina et al. (2022). Stem pests participate in the decomposition of wood of individual branches, parts of trunks and whole trees during feeding, but certain species of xylophagous insects under favorable conditions for reproduction and a sharp increase in the population can cause damage to viable trees, which is confirmed by N. Puzrina et al. (2022) in pine plantings and the results obtained for plantings with a predominance of common spruce.

Pheromone monitoring of forest stands provides information about the presence of

foci of phytophagous insects in the plantings, helps to determine the species composition, number and dynamics of potential expansion of the focus in plantings with an available food base. It becomes possible to determine the rate of population spread and the variability of morphological features of adult insects during the summer period, especially when the population density is low (the initial phase of focus development) and predict the timing of forest protection measures. Among the various forestry measures to reduce economic losses during outbreaks of bark beetle populations, sanitary tree felling is a method that is often practiced both in Europe and in North America, but in Ukraine, the ban on cutting down freshly planted trees during the “silence period” from April 1 to June 15 reduces the effectiveness of control of xylophage insects (Kramarets & Matsiakh, 2018).

The main tasks of using pheromone traps: detection of new foci; establishment of focus boundaries; establishment of the dynamics of phytophagous insect swarm; creation of the so-called “sexual vacuum” and disorientation of males to reduce the number with the help of pheromone traps, that is, violation of pheromone communication between the sexes (Mujezinovic et al., 2023). According to research

by C. Fettig & A. Munson (2020) and M. Braccalini *et al.* (2024), it is possible to use pheromone traps with bark beetle aggregation inhibitors. Notably, the use of pheromones does not pollute the environment, as they are environmentally safe and act selectively on insects of a particular species. However, not all individuals are attracted to artificial pheromones; part of the population is insensitive to them and gives artificial pheromone-resistant offspring that are also resistant to these pheromones, so if traps are used for several years, a significant part of the population may not respond to the pheromone (Fruhbrodt *et al.*, 2023).

Insects were found and identified in the drying foci, including the sharp-dentated bark beetle *Ips acuminatus* Gyll., European spruce

bark beetle *Ips typographus* L., spruce wood engraver *Pityogenes chalcographus* L., synanthropic species *Palorus depressus* Fabricius, and entomophagous *Thanasimus formicarius*. Among them, the largest number of individuals was the European spruce bark beetle. During the entire period of observations of the traps, the capture of an adult European spruce bark beetle in the amount of 10-15 individuals per trap and synanthropic species *Palorus depressus* was recorded singly. Some species of predatory entomophagous, in particular ant beetle *Thanasimus formicarius* L., fell into the traps, and one of the traps contained the tanner beetle *Prionus coriarius* L., but their number was small and did not exceed one individual per trap during the ten-day catch period (Fig. 6).



Figure 6. Entomocomplex of spruce stands

Source: photo by the authors

To determine the degree of settlement of spruce by xylophage insects, model trees were used, each of them was cleaned of knots, and the length of areas of thin and thick bark was determined. Separately, on dry and drying trees, the species composition

was determined and the density of the settlement was taken into consideration, that is, the average number of species of the subfamily *Scolytinae* families *Curculionidae* per square decimeter of the trunk surface was determined (Table 3).

Table 3. Degrees of tree colonization by xylophage insects

Species	Density of settlements, mother galleries per 1·dm ²		Production of stem pests, emergence holes per 1·dm ²	
<i>Ips typographus</i>	22.8±6.4	high	33.6±2.9	high
<i>Pityogenes chalcographus</i>	6.4±0.2	low	32.4±1.2	average
<i>Ips acuminatus</i>	0.3±0.1	low	1.1±0.2	low

Source: compiled by the authors

The identified populations of xylophagous insects are characterized by different degrees of settlement, and they are also observed on trees of different categories, but only very weakened Norway spruce trees contained single specimens of *Ips acuminatus*. The population of *Ips typographus* has the highest settlement density, the number of beetles of the

younger generation or the production of stem pests of which averaged 34 holes per 1 dm² (Fig. 7). Despite the low density of the settlement, *Pityogenes chalcographus* has the ability to attack almost healthy trees and forms continuous mass populations in the surveyed plantings together with the European spruce bark beetle.



Figure 7. Production of stem pests

Source: photo by the authors

The process of degradation of spruce forests is highlighted in a number of studies by forestry scientists back in the 19th-20th centuries (Austara *et al.*, 1986; Christiansen & Bakke, 1989), when global climate warming, anthropogenic air and soil pollution, etc., were not yet noted. According to research by V. Kramarets & I. Matsiakh (2018) xylophage insects have a significant impact on the deterioration of spruce forests after their weakening under the influence of various factors (dry periods, thinning of stands due to logging, etc.). The largest number of species belongs to the family *Curculionidae*, in particular from the subfamily *Scolytinae*, in particular, the spruce tree is actively inhabited by the European spruce bark beetle *Ips typographus* and its accompanying bark beetle species, which is confirmed

by the current study. The researchers note that the drying processes of spruce and other tree species were previously explained as a consequence of the action of a single factor, but in forest biocenoses there is often a complex action of pathogens, ecological groups of insects-phytophagous, and factors of inanimate nature, the influence of which can be significantly modified by protective mechanisms

S. Hofmann *et al.* (2024) identified species-specific features of *Ips typographus*, which contribute to mass outbreaks, include the ability to successfully populate even healthy trees due to intraspecific pheromone communication, high fecundity, and phenological plasticity. *Ips typographus* is a multivoltine bark beetle that can form up to three generations per year. Most of the beetle's life cycle occurs under the

bark, where it reproduces and develops in the phloem. Consequently, the process of development of foci of mass reproduction of xylophage insects includes different phases, each of which differs in the typical population size, which is confirmed by N. Puzrina *et al.* (2022) in studies on pine plantations and current surveys. Population dynamics of *Ips typographus* in space and time, from the phases of low beetle numbers (endemic stage) to population growth and the outbreak stage, and especially in the dispersal stage, it is characterized by the search for a suitable habitat and nutrient plant. According to N. Puzrina *et al.* (2022), near mass breeding areas, where the population size is too large, migration centers are usually formed, where insects migrate to look for new places to settle. Migration foci exist for several years, until the population completely dissipates and does not return to the initial number.

S. Netherer *et al.* (2024) concluded that during the epidemic phase, mass aggregation using sex pheromones leads to rapid colonization of Norway spruce trees (*Picea abies*), which was also noted during the current study of spruce stands. They noted that the European spruce bark beetle is one of the most dangerous spruce pests. It penetrates under the bark of the tree and feeds on its cambial tissues, which leads to the death of the tree. During a drought, when the tree is already weakened, the bark beetle has a better chance of successful settlement and reproduction. In addition, the bark beetle is often a carrier of pathogenic fungi, such as fungi of the genus *Ophiostoma*, which can cause additional damage to the tree. These fungi spread through the vascular system of the tree, which leads to an even greater weakening of the spruce and accelerates its death.

According to the research by P. Lehmann *et al.* (2020), due to climate change, the distribution of most insect species is determined by temperature-dependent population dynamics

and trophic interactions. In a chronic pest focus, insects that attack trees are usually in a phase of increasing or concentrated abundance, due to the formation of populations with reduced density. L. Meshkova *et al.* (2017) note that they are characterized by a relatively moderate level of insect numbers (although it is increased compared to healthy forests) and a limited number of trees that have withered in the current year. Episodic foci, or foci of mass reproduction, are characterized by a short (3-5 years) period of development, a high level of population size and a significant volume of drying trees. In both cases, reversible and irreversible consequences for forest stands are possible, but in the latter case, when mass reproduction of insects occurs, complete destruction of the forest is usually observed.

Thus, the deterioration of the sanitary state of plantings of Norway spruce is the result of a complex impact of various factors, including abiotic and biotic factors, such as pathogens, insects, climate change, and human activity. Forest degradation includes the loss of resistance of trees to various negative factors, such as diseases and pest attacks, and a decrease in wood growth. To prevent environmental threats in spruce stands, it is effective to control pests and pathogens, as well as control and monitoring of xylophage insect populations and their population dynamics using pheromone traps, in particular.

Conclusions

An assessment of the sanitary state of the plantation with a composition of 30% Norway spruce (*Picea abies*) aged 46 years, 20% Norway spruce (*Picea abies*) aged 62 years, 20% Scots pine (*Pinus sylvestris*), 0% European white birch (*Betula pendula*) of natural origin and a slight admixture of European aspen (*Populus tremula*) and common Oak (*Quercus robur*) and it was found that due to the Norway spruce that

prevails in the composition, the plantings are classified as drying with a sanitary state index of IV,05. For *Pinus sylvestris*, this indicator was II,70; for *Quercus robur* – III,68; for *Betula pendula* – III,46; for *Populus tremula* – II,43; for *Alnus glutinosa* – III,32 respectively. For *Picea abies*, the distribution of trees by categories of sanitary state in different diameter classes was compared with the average indicators for the stand, and a significant deterioration in the sanitary state of trees with the smallest (8, 12 and 16 cm, respectively) and the largest (44 cm) diameter class (age 62 years) was found.

During the surveys, insects were identified in pheromone traps, including *Ips acuminatus* with low settlement density (0.3 ± 0.1 mother galleries per 1-dm^2) and the production of young beetles (1.1 ± 0.2 emergence holes per 1-dm^2), *Pityogenes chalcographus* with low settlement density (6.4 ± 0.2 mother galleries per 1-dm^2) and the average production of young beetles (32.4 ± 1.2 emergence holes per 1-dm^2) and *Ips typographus* with the highest

settlement density values (22.8 ± 6.4 mother galleries per 1-dm^2) and production of young beetles (33.6 ± 2.9 emergence holes per 1-dm^2), respectively.

Pheromone monitoring determines the species composition of xylophage insects, the rate of population spread, the variability of morphological features of adult insects during the summer period, and predict the timing of forest protection measures. Therefore, in order to preserve natural complexes and properly maintain the forest fund in an appropriate sanitary state for the implementation of protective, water-regulating, aesthetic and sanitary-hygienic functions of forests, it is necessary to constantly monitor and take a set of measures to improve the sanitary condition.

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None.

Conflict of Interest

None.

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Анотація. Комахи-ксилофаги можуть завдати значної шкоди лісам, викликаючи всихання дерев. Феромонний моніторинг дозволяє вчасно виявити появу цих шкідників і вжити заходів для їх контролю. Мета дослідження полягала у визначенні санітарного стану ялинового насадження та феромонного моніторингу популяцій комах-ксилофагів. Ступінь пошкодження насадження ялини звичайної визначали відповідно до шкали значень індексів санітарного стану як середньозважене значення оцінки розподілу дерев різних категорій стану. За результатами обліків на пробних площах розраховано індекс (середню категорію) санітарного стану ялинового деревостану загалом, встановлено, що найбільш уразливими до патологічних чинників виявилися дерева в найменших (8, 12 та 16 см відповідно) та найбільшому (44 см) ступенях товщини. Використання феромонного моніторингу для оцінки стану лісових насаджень мало на меті виявлення наявності шкідливих організмів на певній території, визначення їх видового складу, чисельності та динаміки розвитку. У лісовому масиві, де було проведено феромонний облік, виявлено та ідентифіковано комах, включаючи вершинного короїда *Ips acuminatus*, короїда-типографа *Ips typographus*, гравера звичайного *Pityogenes chalcographus*, синантропного виду *Palorus*

depressus та хижого мурахожука *Thanasimus formicarius*. Найбільша кількість особин у пастках фіксувалася у короїда-типографа протягом усього періоду спостережень, де на кожную пастку відловлювалося від 10 до 15 особин, а також у синантропного виду *Palorus depressus*. Проаналізовано потенційні можливості розмноження популяції комах-ксилофагів, найбільшу щільність поселення має популяція *Ips typographus*, чисельність жуків молодого покоління або продукція стовбурових шкідників якого становила в середньому 34 отвори на 1 дм². Незважаючи на низьку щільність поселення, *Pityogenes chalcographus* має здатність атакувати практично здорові дерева і в обстежуваному насадженні формує суцільні масові популяції спільно із короїдом-типографом. Отримані результати будуть корисними для моніторингу і контролю шкідників, що дозволить вчасно виявити та оцінити рівень загрози для лісових насаджень

Ключові слова: комахи-фітофаги; облік; феромонні пастки; *Ips typographus*; *Pityogenes chalcographus*

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Effect of the operating environment conditions of wood composites on the adhesive joint strength

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Abstract. To ensure the durability and safe operation of wood composite products, it is necessary to clearly understand how operating conditions affect the adhesive properties of materials. The aim of the study was to experimentally investigate the influence of operating conditions on the change in weight and size of samples with a base of chipboard and medium-density fibreboard, laminated with oak veneer using glues of different degrees of moisture resistance was experimentally investigated. The regularities of these factors effects on the materials and the strength of the glue joint have been established. It was found that the increase in weight of samples with a chipboard base was at the level of 6.25%. For medium-density fibreboard, the value was slightly different and was 4.3%. If the environmental conditions were combined, the indicators of chipboard and medium-density fibreboard samples decreased to 3.72 and 2.99%, respectively. It had also been established that the most stable was glue “Rakoll Express D3”. While the worst performance was demonstrated by the glue “Woodmax WR 13.50M”. The maximum increase in linear dimensions was recorded in chipboard samples with “Rakoll Express D3” glue – 5.25%. Stability coefficients were calculated, indicating a significant decrease in strength, especially under the influence of humidity and temperature at the same time. The least stable was the combination of medium-density fibreboard and “Woodmax WR 13.50M” glue. Instead, the best resistance was demonstrated by the combination of chipboard with “Rakoll Express D3” glue. It was found that the humidity of the environment has a more significant influence on the linear dimensions. The use of wood composites in structures where materials are exposed to changes in temperature, humidity, and ultraviolet radiation is important to ensure the long-term service and reliability of such products

Keywords: wood materials; operating conditions; linear dimensions; wet environment; temperature and humidity fluctuations; destructive pressure

Introduction

As the increase in greenhouse gas emissions due to industrial development accelerates global warming, architecture in the 21st century is moving toward meeting not only structural stability, but also energy efficiency and environmental considerations. Along with reliability, building codes and standards require buildings to be airtight, which helps save energy and avoid structural damage, as well as providing good sound and thermal insulation (Lysenko *et al.*, 2019).

Gluing is an important technological stage of connection in many industries, including furniture. The adhesive joint is gaining more and more interest due to the increasing demand for the combination of disparate structural elements. When two materials are in contact, proper

adhesion between them is essential. Therefore, according to M. Derikvand *et al.* (2021), it is necessary to successfully combine methods of achieving the required joint strength, even between different types of wood materials. A. Pizzi & K.L. Mittal (2018) noted that the main reason adhesion cannot be clearly defined is its very complex nature. Adhesion research over the years has resulted in a more consistent and multidirectional definition of adhesion.

People have long built construction using wooden elements. The large size and uniformity of the properties of Cross Laminated Timber Structures (CLT) panels determine their potential for construction (bearing walls, floors). As with solid wood, CLT structures are significantly affected by the humidity of the environment.

F. Brandstätter *et al.* (2023) showed that moisture transport model can be used to realistically simulate moisture absorption and drying under adverse conditions. The effect of adhesive lines connecting the layers of CLT panels during the experiment on moisture transfer was investigated. It was found that the adhesive line has little effect on the moisture content of the surface layers of CLT, but the effect increases towards the middle layer. However, the environmental conditions of the operation of these panels were not investigated.

Research into the manufacture of bonded structures and their manufacturing processes has contributed to finding ways to make such products cheaper. This approach can provide a significant reduction in overall construction costs. The main aim of the work by P. Resnais *et al.* (2021) was to study the use of residual materials resulting from the processing of CLT panels. That is, assessed the possibility of reprocessing residual materials resulting from the processing of glued wooden structures. During the testing of the panels, two main objectives were realized: to compare the technical characteristics of the remnants of the CLT panels with the classic CLT panel and to evaluate the effect of two types of resins (melamine-urea-formaldehyde (MUF) and polyurethane (PU)) on the structural properties of the recycled CLT materials. Research results show that the recycling of glulam construction waste can give good results, and the waste of CLT panel production can be successfully used in construction, reducing the cost of CLT panel production. However, the influence of operating environment conditions on such products has not been investigated.

Many studies have been directed to the modification of adhesive compositions. Thus, V.G. Ravindra (2023) investigated the effect of adding N-methylol acrylamide (NMA) co-monomer to PVA-based wood glue on water resistance and thermal stability. Compared with the

traditional water-resistant wood adhesives, the water resistance of the polymer-based starch-stabilized PVAc-NMA emulsion adhesive was similar to that of the PVA-stabilized PVAc-NMA emulsion-based adhesive. The cross-linking reaction between the amide groups of the copolymer chain and the hydroxyl groups of aluminium chloride and starch and PVA forms a cross-linked structure, which occurs quickly at room temperature, according to Fourier transform infrared analysis. The effectiveness of starch-stabilized PVA-NMA wood adhesives was evaluated by measuring the shear stress of wood joints in water according to the EN 204:2002 (2002), EN 205:2003 (2003) D3 standard. The starch-modified adhesive demonstrated superior water resistance, mechanical strength characteristics, and geometric stability in contrast to cross-linked stabilized PVA wood adhesive.

The use of dry powder mixtures of polyester resins is encouraged in adhesive structures using environmentally safe technology. As a result of experimental studies by S. Mazurchuk *et al.* (2023), proved the convenience of plywood production based on dry adhesive mixtures of polyester resins was substantiated. The strength limit of the surface layer of plywood was proven to exceed 1.2 times the standard value for plywood pressed at 200°C and 1.04 times the standard value at 240°C. With regard to the chipping strength of the adhesive layer of the plywood, an improvement was observed. The obtained indices exceeded the standard values after dry exposure and after dipping for both types of plywood – 2.13, 1.86, 1.88 and 1.73 MPa at the standard 1.5 MPa. The chemical changes in the wood during pressurization at high temperatures were not analysed.

The chipboard industry cannot meet the needs of the market, so fillers have been used to save raw materials. Also, their use helps to change the properties of plates and expands

the scope of their use. M.E. Ergun *et al.* (2023) investigated the effect of adding different proportions of activated carbon (0, 1.5, 4.5 and 7.5%) on the physical properties (density, moisture content, swelling in thickness and water absorption) of chipboard. As a result, it was found that the density became greater and the water content decreases with an increase in the content of activated carbon. This indicates improved dimensional stability and water resistance. The mechanical properties (internal joint strength, modulus of rupture, and modulus of elasticity) are significantly improved with the addition of activated carbon. The actual analysis showed that the addition of activated carbon reduced in mass loss by 6.15% compared to the control group. There is no data on the surface characteristics of the material and the ability to joint with other materials.

Usually, products made of wood and wood materials are within wide limits of temperature and humidity conditions of the environment. Their surface can be protected by applying paint and varnish materials, including oil-waxes. This measure slightly extends the service life of the products. It is also possible to apply adhesive compositions of various degrees of resistance, which will ensure the dimensional stability of the elements and reliability. In this regard, there is a need to establish the physical and mechanical parameters of the adhesive layer depending on the influence of various environmental factors, which determined the need to conduct this study.

Based on the analysis of literary sources, it

was established that not only the characteristics of wood or wood materials are important for the manufacture of a durable construction or product. The technical parameters of the applied glues also affect the strength of the elements due to the formation of stable adhesives. Adhesive compositions should be characterized by non-toxicity, economic efficiency, easy application and resistance to atmospheric influences. These provide the basis for conducting studies to determine the parameters that warrant the use of wood and wood material adhesives in the manufacture of various products.

The aim was experimental substantiation of the stability of the adhesive joint based on glues of different degrees of water resistance under the influence of temperature and humidity changes. To achieve the aim, the task was set to conduct a set of this research to determine the influence of the operating environment of the product on the change in physical characteristics and strength of the adhesive layer.

Materials and Methods

The choice of material for facades and furniture frames has a significant impact on the quality and appearance of the final product. Medium-density fibreboard (MDF) and chipboard have their advantages and are used in various products. For the study, these two bases were faced with oak veneer using three brands of glues – Rakoll Express (D3) (Germany), Rakoll ECO-4 (D4) (Germany), Woodmax WR 13.50M (D3) (WR) (Poland) – which were chosen based on the prioritization method (Table 1).

Table 1. The final matrix for calculating the complex priority of glue

Glue brand	Glue priority according to indicators					Indicator priority		Comprehensive priority
	1	2	3	4	5	number	value	
Rakoll Express D3	0.26	0.22	0.27	0.23	0.20	1	0.17	0.24
Rakoll ECO-4	0.13	0.20	0.23	0.23	0.16	2	0.15	0.19
FOLLMANN FOLCO LIT D4 W91	0.17	0.20	0.18	0.23	0.17	3	0.20	0.19

Table 1, Continued

Glue brand	Glue priority according to indicators					Indicator priority		Comprehensive priority
	1	2	3	4	5	number	value	
FOLLMANN FOLCO LIT X 3000	0.17	0.20	0.18	0.16	0.25	4	0.26	0.19
Glue Woodmax WR 13.50M, class D3	0.26	0.18	0.14	0.14	0.22	5	0.22	0.18

Note: 1 – glue viscosity, mPa·s; 2 – density, kg/m³; 3 – consumption norm, g/m²; 4 – minimum pressing time, min.; 5 – price

Source: compiled by the authors

Glue was applied with rollers for a more uniform distribution of glue. Gluing took place on a vacuum press – holding for 15 minutes at a temperature of 55 °C, pressing pressure of 0.7 atm. (Fig. 1). After technological aging, the pressed plates were cut into samples of 50×50 mm size.



Figure 1. Preparation of samples

Note: a – pressing of plates, b – cutting of experimental samples

Source: compiled by the authors

For experiments, the samples were divided into 5 groups and labelled accordingly (Fig. 2).

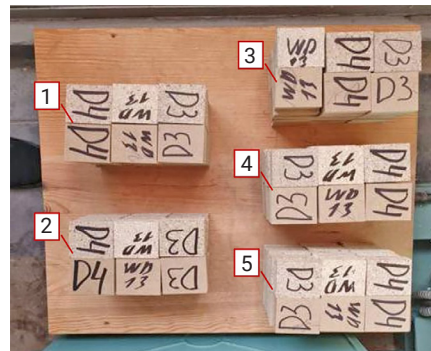


Figure 2. Experimental samples with an MDF/chipboard base are faced with oak veneer using glues of various degrees of water resistance

Note: 1 – control samples; 2 – aging in conditions of high humidity; 3 – at elevated temperature (+80°C); 4 – at low temperature (-15°C); 5 – combined influence of environmental conditions (humidity, high and low temperature)

Source: compiled by the authors

During the experiment, a comprehensive approach was employed to experimentally determine the effectiveness of the adhesive joint by examining the resistance of the adhesive layer to degradation following exposure to varying temperature and humidity conditions. The testing method for resistance to atmospheric fluctuations involved simulating the effects of external environmental conditions on the stability of the adhesive layer to assess changes in evaluation metrics before and after the temperature and humidity

alterations. The test cycle of changes in temperature and humidity fields on the adhesive layer of wood included several stages (Fig. 3). At the beginning, the samples were moistened with a sprayer and kept at a temperature of $20 \pm 2^\circ\text{C}$ and a relative humidity of $97 \pm 3\%$ for 6 hours. Then holding at a low

temperature $-15 \pm 3^\circ\text{C}$ for 6 hours. Then conditioning at a temperature of $20 \pm 2^\circ\text{C}$ and a relative humidity of $65 \pm 3\%$ for 6 hours. At the end of keeping the samples at a high temperature $80 \pm 2^\circ\text{C}$ for 6 hours. Each stage was accompanied by weighing and measuring the dimensions of the samples.



Figure 3. Exposure of experimental samples in different temperature and humidity conditions

Note: a – humid environment, b – high temperature ($80 \pm 2^\circ\text{C}$), c – low temperature ($-15 \pm 3^\circ\text{C}$)

Source: compiled by the authors

To determine the operational stability of the adhesive layer, the strength of the connection during chipping and the influence of environmental factors on this indicator were determined. Determination of the amount of moisture absorption by the samples was carried out according to the method, the essence of which was the periodic determination of the amount of absorbed moisture after exposure in different temperature and humidity conditions (Tsapko *et al.*, 2022).

Determination of the strength of adhesive layers was carried out in accordance with ISO 9653:1998 (1998).

Results and Discussion

During the exposure of the samples in different climatic conditions, the change in their humidity at the end of each cycle (the duration of the cycle is 6 days) was determined. For greater convenience, the average values for each of the groups were calculated (Table 2).

Table 2. Change in weight of samples in different environmental conditions

Operating environment conditions	Glue	Weight, g									
		initial value	1 cycle	2 cycle	3 cycle	4 cycle	initial value	1 cycle	2 cycle	3 cycle	4 cycle
		chipboard					medium-density fibreboard				
The humidity of the environment (97%)	D3	28.17	29.28	29.39	29.70	29.98	33.31	33.83	33.98	34.41	34.63
	D4	28.42	29.36	29.64	30.12	30.14	34.20	34.83	35.39	35.51	35.83
	WR	28.36	29.37	29.76	29.97	30.14	33.11	33.59	34.02	34.19	34.49

Table 2, Continued

Operating environment conditions	Glue	Weight, g									
		initial value	1 cycle	2 cycle	3 cycle	4 cycle	initial value	1 cycle	2 cycle	3 cycle	4 cycle
		chipboard					medium-density fibreboard				
Ambient temperature (+80°C)	D3	28.41	27.18	26.91	27.02	27.98	33.71	32.41	32.15	32.25	33.03
	D4	28.55	27.34	27.10	27.22	28.13	34.43	33.21	32.92	33.06	33.87
	WR	29.50	27.91	27.63	27.78	28.77	33.19	31.82	31.56	31.69	32.54
Ambient temperature (-15 °C)	D3	28.30	28.33	28.29	28.28	28.00	33.51	33.53	33.55	33.45	33.28
	D4	28.56	28.66	28.61	28.54	28.38	34.02	34.23	34.23	34.14	34.00
	WR	29.04	29.00	28.78	28.87	28.63	32.94	32.92	32.94	32.84	32.70
Combination of environment parameters	D3	28.40	27.54	27.65	27.19	27.47	33.55	32.52	32.50	32.21	32.45
	D4	28.83	27.87	27.99	27.54	27.81	34.27	33.42	33.49	33.07	33.35
	WR	29.34	28.14	28.27	27.77	28.06	33.23	32.25	32.39	31.93	32.24

Source: compiled by the authors

Analysing the results of the Table 2, it is noted that in conditions of high humidity, an increase in the weight as of chipboard and MDF samples is observed. The largest weight increase occurs in chipboard samples – 6.25% versus 4.3% for MDF. When the samples are kept at a high temperature, a predicted decrease in weight is observed. However, towards the end of the experiment, a slight increase in the weight of chipboard and MDF samples is observed, which may mean some problems in observing the conditions of the experiment. In general, the weight of the samples decreased by only 1.84%. At low temperatures, the weight of the samples practically does not change (the mass decreases by 0.77%). Under combined

environmental conditions, chipboard and MDF samples show a decrease in weight by 3.72 and 2.99%, respectively.

In general, the humidity of the environment has the greatest influence on the change in the weight of the samples. Thus, the conducted studies allow us to conclude that chipboard and MDF are sensitive to the influence of the humidity of the environment, which leads to the absorption of moisture by the material, an increase in its weight and the stability of the adhesive layer. Also, during the experiment, the dimensions of the experimental samples were fixed. The percentage change in the linear dimensions of the samples was determined (Table 3).

Table 3. The influence of environmental conditions on the change in the linear dimensions of the samples

Operating environment conditions	Glue	Change of linear dimensions, [%]					
		chipboard			MDF		
The humidity of the environment 97%	D3	+0.20	+5.25	+0.33	+0.07	+2.99	0.00
	D4	+0.15	+4.44	+0.22	+0.10	+4.28	+0.08
	WR	+0.18	+2.94	+0.10	+0.08	+3.85	+0.07
Ambient temperature (+80°C)	D3	-0.17	-1.20	-0.15	-0.18	-2.02	-0.13
	D4	-0.13	-0.97	-0.12	-0.39	-1.54	-0.12
	WR	-0.05	-2.10	-0.28	-0.23	-0.88	-0.12

Table 3, Continued

Operating environment conditions	Glue	Change of linear dimensions, [%]					
		chipboard			MDF		
Ambient temperature (-15 °C)	D3	-0.02	-0.60	-0.13	-0.03	-0.60	-0.03
	D4	+0.02	-0.55	-0.02	-0.07	-0.79	-0.15
	WR	+0.08	-0.74	-0.08	-0.03	-0.69	-0.03
Combination of environment parameters	D3	+0.01	-0.56	-0.10	-0.16	-2.31	-0.02
	D4	-0.06	-0.61	0.00	-0.19	-2.07	-0.10
	WR	-0.12	-1.36	-0.27	+0.08	-2.02	-0.07

Source: compiled by the authors

In a wet environment there is an increase in the linear dimensions of samples for all types of glue and materials. The largest increase was noted in samples with a chipboard base with D3 glue (up to 5.25% along the length). At an elevated temperature, the size of the samples decreases for all variants of the samples. The largest decrease is observed for MDF with D4 glue (up to 2.07% in width). At low temperatures, changes in size are insignificant – they range from 0-0.08%. Under the conditions of combined influence (humidity and different temperature values), slight changes in dimensions are observed, mainly a decrease in the range of 0-0.27%.

In general, samples glued with WR are more stable. And samples with a chipboard

base show greater sensitivity to changing conditions than with MDF. The largest change in linear dimensions occurs in the thickness of the samples, because the inner layer of sheet materials is usually less dense than the outer ones. At the same time, the amount of changes in the bases is different, which is due to the difference in the structure of the materials. Namely, the size of the chip fraction used in the inner layers of chipboard and the more uniform fibre structure of MDF.

With regard to the main experiment (determination of the destructive pressure on the adhesive joint after exposure of the samples in different climatic conditions using a tearing machine) – a visual assessment of the fracture surface after loading is shown in Figure 4.

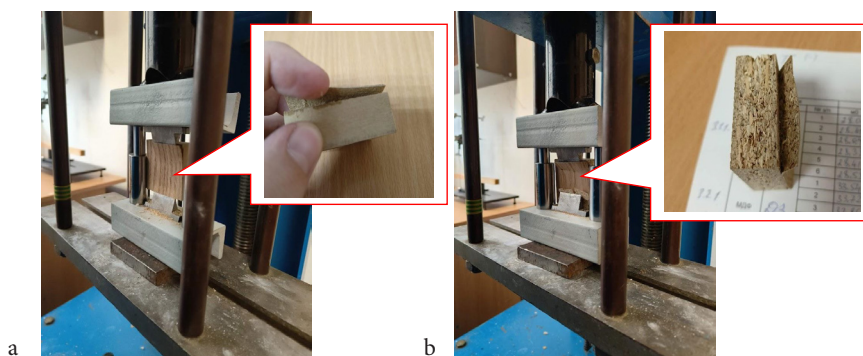


Figure 4. Pressure of samples in the tearing machine during determination of the strength limit of the adhesive joint

Note: a – MDF base; b – the base of chipboard

Source: compiled by the authors

The nature of the destruction for samples with different bases is slightly different. In samples with a chipboard base, veneer destruction is observed under a certain pressure, while in samples with MDF, the veneer remains intact. This is explained by the different density of these materials.

On the peeled veneer, the base material remains over the entire area, which indicates strong adhesive connections regardless of the

conditions before the experimental exposure of the samples. The nature of the destruction of the samples mainly occurred along the material of the base, with separation of the outer layer of the base to the veneer. Only in some cases was veneer destruction observed.

The indicators of the destructive pressure on all groups of samples are shown in Figure 5 in the form of diagrams for visual comparison.

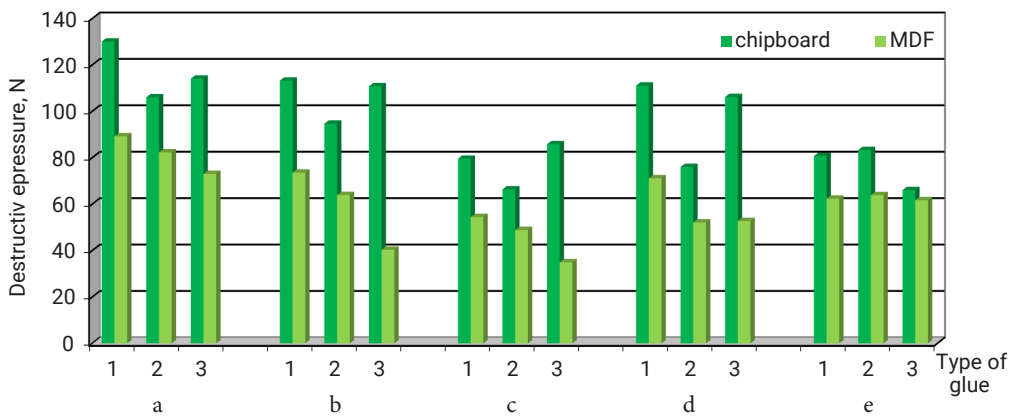


Figure 5. The maximum breaking load of test samples

Note: 1 – glue D3; 2 – glue D4; 3 – glue WR; a – control; b – after exposure in a humid environment; c – after exposure to elevated temperature; d – after exposure in a freezer; e – a combination of temperature and humidity conditions

Source: compiled by the authors

Analysing the obtained results, it was established that for the control samples, the highest destructive pressure was recorded for chipboard with D3 glue (130.03 N), and the lowest for MDF with WR glue (72.99 N). In conditions of high humidity, the pressure on the adhesive joint decreased for all samples, except for chipboard with WR. The biggest decrease in MDF with WR glue is 45%. At elevated temperature, a decrease in the value of the destructive

pressure is also observed for all samples. The biggest decrease – 34% – in samples with a chipboard base with D3 glue. In conditions of low temperature, the pressure decreased not so significantly, by a maximum of 18% for chipboard with D4 glue. With the combined effect of the factors, the largest load reduction in chipboard with WR glue is by 42%. Stability coefficients were calculated to determine the influence of environmental factors (Table 4).

Table 4. Indicators of stability of the adhesive seam depending on the operating environment

Research samples		The influence of environmental conditions on the stability of the adhesive joint			
Basis	Type of glue	humidity	high temperature	low temperature	combination of parameters
Chipboard	D3	0.87	0.61	0.85	0.62
	D4	0.73	0.51	0.58	0.64
	WR	0.85	0.66	0.82	0.51
MDF	D3	0.82	0.61	0.80	0.70
	D4	0.72	0.55	0.58	0.72
	WR	0.45	0.39	0.59	0.69

Source: compiled by the authors

If the glue is not heat-stable enough, the glued joint may fail to maintain its adhesion. J. Vaněrek *et al.* (2024) studied the behaviour of glued joints based on phenol-resorcinol-formaldehyde (PRF), polyurethane (PUR) and emulsion polyisocyanate (EPI) under the influence of long-term and short-term elevated temperatures. Calorimetric analysis revealed that the onset of thermal degradation occurred at 135°C for EPI and around 160°C for both PRF and PUR.

Therefore, the toughness of the adhesive joint is negatively affected by both increased humidity and the temperature of the environment, especially the combination of temperature and humidity conditions. The combination of MDF base and WR glue turned out to be the least stable. Instead, the best stability was demonstrated by combining the chipboard base with D3 glue.

The applications of wooden structures are quite varied, as they are utilized in the construction of external walls and roofs, window frames, and doors, suitable for both dry and wet environments. Research conducted by S. Dabin & K. Keonho (2022) on the impact of the production environment on the effectiveness of bonding cross-laminated timber (CLT) with polyurethane (PUR) adhesive demonstrated that adjusting the pressing time based on the adhesive's open time significantly enhances adhesive strength under production conditions. The peeling tests performed under consistent

relative humidity and adhesive conditions revealed that the temperature of the production environment affects the reliability of the glue.

Strengthening structural elements with the help of reinforcing tapes is a widely adopted technique of increasing the durability of buildings. Here, the most important element is the adhesive layer, which is involved in the stresses transfer between the aggravated element and the reinforcing tape. Studies A. Szezwczak (2021) show the possibility of changing the adhesive's bonding strength by changing composition and application surface of the adhesive. The results obtained from the tests suggest that the method of surface modification, along with the outlined adjustments, can be tailored to the specific conditions of adhesive application. Similar reinforcement was carried out by Í. Yalçın & R. Esen (2023) with industrial wood species. Was found that the type of glue and the process of lamination have a positive influence on the mechanical properties of the material. The essence of this method is to first compress the wooden boards for 10 minutes and then perform lamination. Fiberglass and carbon fibre are suitable as reinforcing elements.

Also, increasing the adhesion strength and water resistance of wood glue can be achieved by varying the SPI concentration, pressing temperature, and pressing time. D. Vnučec *et al.* (2016) thermally modified commercial SPI

in a vacuum chamber at 50°C. Distilled water dispersions with SPI mass fractions of 9.09, 9.91, 10.71, 11.50, and 12.28% were prepared. The effective penetration (EP) and tensile shear strength of beech wood samples jointed under the same gluing conditions (in accordance with European standards EN 204 and EN 205) were evaluated. It has been found that the viscosity of the glue increased with increasing SPI concentration. EP rose with increasing viscosity and SPI mass fraction up to 11.50%, after which it started to decline. The optimal pressing temperature determined for this glue was 110°C, with an optimal pressing time of 10 minutes.

In the course of the experiment, it was established (Fig. 5, Table 4) that, regardless of the glue, samples with MDF as a base withstand less pressure than samples with chipboard (the reason for this effect is discussed above), in general, this difference is 35.38%. Based on the results, it became possible to evaluate the influence of different environmental parameters on the change in the linear dimensions of samples with different materials and adhesives (Table 3). The combination of MDF and WR glue turned out to be the most stable.

In order to reduce water absorption, thermal modification of curd is widely practiced today. In particular, the possibility of using various cellulose-containing materials for the manufacture of furniture panels is being investigated. Therefore D.P. Ribeiro *et al.* (2020) evaluated the effect of different levels of heat treatment (170, 200 and 230°C) on the properties of plates made from sugar cane. The experimental panels were evaluated according to their physical (density, degree of compression, moisture, water absorption and swelling) and mechanical (internal connection, tensile strength modulus, flexural modulus) properties. Thermal treatment of cane at 230°C contributed to a significant improvement in the quality of plates. A decrease in water absorption and swelling of

the panels in thickness and an increase in the values of the modulus of elasticity were observed. This result confirms the great potential of using 230°C processing for the production of sugarcane slabs.

In accelerated climate aging tests, components are often subjected to multifactor loading. An example of such climatic stress is ripening at high temperatures and humidity (Yang *et al.*, 2021). During the experiment, the connections are subjected to climatic loads from thermal shocks and the influence of high temperature and humidity. As a result, it was found that the dominant aging factor depends on the type of glue.

The humidity of the environment has a significant effect on the strength of the adhesive connection. In all cases, there is a decrease in strength compared to the control samples. The biggest decrease is for MDF with WR glue (by 55%).

Indeed, wood-based products typically face significant limitations regarding water exposure. In their work, R. Magalhães *et al.* (2021) investigated the influence of the plate humidity on its physical and mechanical properties. Medium-density fibreboard (MDF) from different European manufacturers were stored for 9 weeks under specific conditions (approximate temperature range 15-20°C and 50-85% RH). A notable correlation between the moisture content of MDF and the internal strength of the glue joint was identified, revealing a decreasing linear relationship. It was also observed that this effect is reversible – upon drying, the strength of the internal joint increases again.

Interesting in this direction are the studies of various modifications of oriented strand board (OSB). T. Pipíška *et al.* (2020) acetylated spruce (*Picea abies L. Karst*) fibers using acetic anhydride or thermally modified at 180°C. It was established that the equilibrium moisture content of boards with a modified outer layer did not differ from reference boards. Acetylated

chipboard and cork particle board had a significant increase in water resistance. Acetylation increased the strength of the internal joint. The results provide a comparison between different chipboard modifications and show a new opportunity to reduce the impact of water on chipboard.

Thus, the analysis of adhesives of different degrees of moisture resistance and experimental studies to determine the effects of temperature and humidity fluctuations on the glued layer and the maximum destructive force indicate changes in the characteristics of the adhesive joint. The following studies will allow to investigate the transformation of the surface of the adhesive contact of wood and wood materials, which is destroyed under the affect of temperature and humidity instability. It is also advisable to determine those parameters that significantly influence the beginning of the conversion process of the destruction of the adhesive layer. A promising research direction is establishing the processes of interrelation between the constituent components of glues and their properties of glues, as well as their influence on processes of adhesion with wooden materials and the long life of the product.

Conclusions

The largest percentage increase in mass occurs in chipboard samples (6.25% versus 4.3%). At the same time, the action of frost showed the least impact (the weight of the samples decreased by 0.77% on average).

Likewise, the influence of humidity on linear dimensions was significantly greater than the influence of temperature or their combination

(3.96% on thickness and 0.13% on planar dimensions). A change in size in terms of thickness was noted, while the indicators for chipboard and MDF are slightly different. This is due to the difference in the structures of these materials.

Elevated temperature also leads to a noticeable weakening of the strength of the adhesive joint. The greatest decrease in the stability factor is observed for MDF with WR glue (by 61%). The effect of low temperatures is less noticeable, but also leads to a reduction in the fastness of the seam by 15-42%, depending on the base material and glue. The combined action of humidity and temperature changes has a strong negative impact. The greatest reduction in the stability factor is observed for chipboard with WR glue (by 49%).

Therefore, the comprehensive research carried out in the work made it possible to assess the degree of influence of typical operating conditions of furniture in the kitchen on the strength of the adhesive joint and justify the optimal choice of base materials and glue to ensure the necessary strength and durability of the products. In future studies, it is worth expanding the list of researched wood composite materials that were not included in this work. It is also advisable to modify the coating material using various methods and determine the positive or negative impact of the measures taken on the durability of the finished product.

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None.

Conflict of Interest

None.

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Вплив умов середовища експлуатації деревних композитів на міцність адгезійного з'єднання

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Анотація. Для забезпечення довговічності та безпечної експлуатації виробів із деревних композитів необхідно чітко розуміти, як умови експлуатації впливають на адгезійні властивості матеріалів. Метою роботи було експериментально дослідити вплив умов експлуатації на зміну маси та розмірів зразків в основі яких деревиностружкова (ДСП) та середньої щільності (MDF) плита, шпонованих дубом з використанням клеїв різного ступеню вологостійкості. Встановлено закономірності впливу даних факторів на матеріали та міцність клейового з'єднання. Виявлено, що збільшення маси у зразків з основою ДСП на рівні 6,25 %. Для MDF значення дещо відрізнялося і становило 4,3 %. При поєднанні впливу умов середовища на зразки ДСП і MDF показники зменшувалися до 3,72 та 2,99 % відповідно. Також встановлено, що найстійкішим був клей «Rakoll Express D3». Тоді як найгірші показники продемонстрував клей «Woodmax WR 13.50M». Максимальне збільшення лінійних розмірів зафіксовано у зразків ДСП з клеєм D3 – 5,25 %. Розраховано коефіцієнти стійкості, що свідчать про значне зниження міцності особливо під впливом вологості та температури одночасно.

Найменш стійким було поєднання MDF та клею WR 13.50M. Натомість комбінація ДСП і клею D3 виявилася найкращою. Виявлено, що на лінійні розміри більш вагомим фактором впливу була вологість середовища. Використання деревних композитів у конструкціях, де матеріали піддаються впливу змін температури, вологості та ультрафіолетового випромінювання, є важливим для забезпечення тривалої служби та надійності таких виробів

Ключові слова: деревні матеріали; умови експлуатації; стабільність геометричних розмірів; вологе середовище; коливання температури та вологості; руйнівне навантаження

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Study of agroforestry methods and techniques for soil erosion prevention on agricultural land

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Abstract. The study aimed to identify key factors and mechanisms for the improvement of soil and agroecosystem resilience by using agroforestry technologies in a changing climate. The impact of forest shelterbelts, crop mixing technologies and spatial planning techniques on restoring

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degraded lands and improving ecosystem functions was addressed. The research methodology was based on the synthesis and analysis of data from various scientific sources, and the use of theoretical models and field observations. Regions of Ethiopia, Kenya and Malawi were addressed in the analysis of the effects of multi-level forest belts and mixed crops on reducing erosion, improving soil structure and restoring biodiversity. The results of the study demonstrated that agroforestry interventions in these countries significantly reduced the intensity of water and wind erosion, improved soil water-holding capacity and restored the hydrological cycle. Forest belts increased moisture storage in arid regions of Ethiopia, improved crop yields by creating a favourable microclimate in Kenya, and protected rangeland ecosystems from degradation in Malawi. These interventions also increased soil organic carbon content, reducing the need for mineral fertilizers and minimizing anthropogenic impacts on the environment. The findings confirm the versatility of agroforestry approaches for land restoration and adaptation to climate change. The results demonstrated the importance of integrating agroforestry technologies into sustainable natural resource management systems, which emphasizes the need for scaling up in regions prone to land degradation, including the Kyrgyz Republic

Keywords: forest plantations; spatial planning; ecosystem services; land restoration; water balance management

Introduction

Agroforestry is one of the most promising technologies for sustainable land management and restoration of degraded ecosystems. Modern climate change, intensification of agricultural production and increased anthropogenic pressure on natural systems significantly increased soil erosion, which in turn has a negative impact on productivity and ecosystem functions.

The research relevance of the issue is determined by the global nature of the problem of land degradation, which affects both agricultural areas and natural ecosystems. Current trends in land use intensification, urbanisation and climate change substantially increased soil erosion, which negatively impacts soil productivity, environmental sustainability and the ability to support ecosystem functions (Kerimkhulle *et al.*, 2023; Santosa *et al.*, 2024). This creates serious environmental, social and economic risks.

Soil degradation is caused by a combination of natural and anthropogenic factors. Water

erosion associated with intense precipitation and surface runoff leads to the loss of topsoil, which is rich in nutrients. Wind erosion, typical for steppe and arid regions, is exacerbated by the lack of vegetation cover, blowing away the fertile layer and deteriorating the soil structure. These processes not only reduce the agronomic value of soils but also exacerbate climate change through the release of carbon dioxide stored in the soil profile. Agroforestry is the subject of intensive research in scientific circles due to its significant role in protecting soil, restoring degraded land and increasing the sustainability of agroecosystems. A. Kaur *et al.* (2023) analysed the role of agroforestry systems in soil conservation and sustainable agricultural production. The study highlighted the employment of forest belts as the primary way to reduce soil loss and increase water retention capacity.

M.K. Jhariya *et al.* (2022) also addressed the management of soil organic carbon in agroforestry systems. They emphasised that the

accumulation of organic carbon in the soil not only improves soil structure and fertility but also contributes to the restoration of degraded land. M.T.S. Budiastuti *et al.* (2021) studied agroforestry as a vegetation management strategy to combat forest degradation in Indonesia. This study highlighted that the integration of woody and herbaceous plants into forest ecosystems reduces erosion losses and helps stabilise ecosystem processes. B.C. Rodríguez *et al.* (2022) addressed the use of legumes in agroforestry systems. The study emphasises that such plants are central to strengthening the sustainability of soil systems.

D. Jinger *et al.* (2023) analysed the restoration of degraded land in India by introducing agroforestry. Furthermore, the authors emphasised that forest belts contribute to the restoration of biodiversity by providing habitat for different species of organisms. T.J. Sauer *et al.* (2021) analysed agroforestry practices for soil protection and sustainable agriculture. The study highlighted the significance of such systems for increasing the resilience of agricultural land to climate change. S. Kumar *et al.* (2024) considered agroforestry as a sustainable way to combat the climate crisis and increase the productivity of agricultural land. S. Kumar *et al.* highlighted that the integration of woody and shrubby plants into agricultural landscapes helps stabilise soils, improve water retention capacity and restore ecosystem services such as the hydrological cycle. Moreover, T. Plieninger *et al.* (2020) investigated the impact of agroforestry systems on sustainable landscape management. The study concluded that such systems help conserve biodiversity, improve ecosystem services and restore degraded lands. D.A. Martin *et al.* (2020) explored how land use history affects ecosystem services and the conservation value of tropical agroforestry systems. The study demonstrated that such systems have high potential to restore

ecosystem functions, improve soil health and maintain natural balance in regions with intensive land use. M. Ghimire *et al.* (2024) reviewed agroforestry systems, addressing their role in improving food security and supporting rural livelihoods. The study confirmed that forest belts play a key role in protecting soil, restoring structure and increasing the productivity of agricultural systems.

The aim of this study was to analyse the potential of agroforestry systems in protecting soil, restoring degraded land and improving ecosystem functions. The objectives of the study were to analyse the effectiveness of forest shelterbelts and mixed crops in reducing soil erosion, to examine their role in restoring biodiversity and ecosystem services, and to evaluate spatial planning techniques for adapting agroforestry measures to different climatic conditions.

Materials and Methods

For this study, data for the year 2023 were analysed to incorporate current indicators of the effects of agroforestry on soil health in Ethiopia, Kenya and Malawi (Nkansah-Dwamena, 2023; Koné & Galiegue, 2023; Dagar *et al.*, 2024). This time interval was chosen to assess recent changes and the effectiveness of interventions in the short term. This time interval was chosen to analyse recent changes and assess the sustainability of the results in the relatively short term.

This study was based on the generalisation and analysis of existing scientific data related to agroforestry as an effective method of soil erosion control and restoration of ecosystem functions. The main objective was to systematise knowledge on the role of agroforestry in reducing land degradation, increasing soil productivity and strengthening ecosystem resilience. For this purpose, literature sources including research results, and data on the practical application of the methods were analysed (Kraft *et al.*, 2021; Singh & Singh, 2024).

Theoretical models based on digital elevation maps and climatic data were used to ensure the representativeness of the analyses (Amin *et al.*, 2023). Optimal forest strip patterns on slopes, hilly terrain and flat areas were investigated. Multilevel strips incorporating woody, shrub and herbaceous plants were studied, as well as crop mixing technologies aimed at enhancing the ecological functions of agroforestry systems.

An important part of the study was to investigate the environmental issues of land degradation. For this purpose, existing data on water and wind erosion, extent and impact on agricultural areas were analysed (Panagos *et al.*, 2021). A data systematisation method (Systematization of statistical data and..., 2022) was used for the study to analyse the main erosion factors such as intensive tillage, lack of vegetation cover and climate change. This approach provided an assessment of the potential of agroforestry in reducing soil degradation and greenhouse gas emissions by reducing organic carbon content.

A comparative analysis method was used for the study to compare data on the functions of forest shelterbelts from different sources and regions (Kaluza, 2023). This approach ensured the identification of patterns in the effectiveness of forest strips to prevent soil erosion, improve water balance and reduce wind speed. Comparison of the data assessed the versatility and adaptability of forest belts to different landscape and climatic conditions. To analyse the effectiveness of agroforestry measures, a modelling method (Vayansky & Kumar, 2020) was used to predict the effect of forest strips and crop mixing technologies on reducing erosion and restoring soil water balance. This method was used to study the long-term impact of agroforestry measures on agroecosystems under different natural and climatic conditions. To clarify theoretical data on the ecological

benefits of agroforestry reclamation, the study used a field evaluation method (Field studies, 2024). This approach included observations and data collection in areas with field-protected forest strips in different natural-climatic zones. The field assessment allowed to study the impact of forest strips on soil moisture retention, stabilisation of groundwater table and reduction of dependence on artificial irrigation.

Soil moisture, surface runoff rate and vegetation condition were recorded during field studies. Observations were conducted both in arid regions, where special attention was paid to the ability of forest strips to reduce evaporation and increase soil water storage, and in zones with high erosion levels, where their role in protecting the fertile layer was assessed.

Results

The efficiency of agroforestry as an erosion control method. Scientific evidence confirms that the creation of shelterbelts improves soil physicochemical properties, including increased humus content, water retention capacity, and restoration of microbial activity (Kraft *et al.*, 2021; Singh & Singh, 2024). These changes help reduce greenhouse gas emissions by enhancing carbon storage in the soil profile (Yang *et al.*, 2024). An analysis of the literature has also shown that improving soil structure as a result of agroforestry activities has a positive impact on the restoration of ecosystem functions, such as regulating the hydrological cycle and increasing soil biological activity (Forest and landscape restoration and..., 2022; Shlapak & Zvorska, 2024).

The analysis of the data presented in Table 1 demonstrated a significant positive impact of agroforestry on key soil parameters in Ethiopia, Kenya and Malawi (Amin *et al.*, 2023). Before the introduction of agroforestry, the level of water erosion in these countries ranged from 16 to 18 tonnes per hectare per year, indicating a

high degree of topsoil loss. After the measures, the values decreased to 5-7 t/ha per year, which indicated a 60-70% reduction in erosion. This

reduction was attributed to the creation of forest belts that slowed down surface water runoff and improved soil structure.

Table 1. Efficiency of agroforestry as an erosion control method

Parameter	Ethiopia (before agroforestry)	Ethiopia (after agroforestry)	Kenya (before agroforestry)	Kenya (after agroforestry)	Malawi (before agroforestry)	Malawi (after agroforestry)
Level of water erosion (t/ha per year)	18	7	16	6	17	5
Organic carbon content (%)	1	1.8	1.1	1.9	1.2	2
CO ₂ emissions (t/ha per year)	3	1.5	2.8	1.3	2.9	1.4
Water retention in the soil (mm per m ²)	110	150	115	158	112	160
Soil biological activity (soil health)	0.6	1.3	0.7	1.5	0.6	1.4

Source: compiled by the authors based on the Systematization of statistical data and the development and application of a methodology for assessing the impact of the use of the intellectual property system (2022), J.C. Dagar *et al.* (2024)

The organic carbon content of soils before the interventions was low, indicating land degradation. In Ethiopia, Kenya and Malawi, it was 1%, 1.1% and 1.2%, respectively. After the introduction of agroforestry measures, this figure increased to 1.8%, 1.9% and 2%. This increase of 50-67% is due to the accumulation of organic matter, which has restored soil fertility and improved carbon storage properties.

Before the measures, carbon dioxide emissions were at the level of 2.8-3 tonnes per hectare per year, which indicated a significant impact on the climate. After agroforestry, these figures decreased by more than 50%, reflecting an increase in soil carbon storage and an overall improvement in soil condition. This was made possible by planting trees and shrubs that effectively sequester carbon and prevent its release into the atmosphere. Water retention in the soil has also improved significantly. In Ethiopia, Kenya and Malawi, before the project, they were 110-115 mm/m², and afterwards they increased to 150-160 mm/m². The 30-40% increase in moisture availability for plants is particularly important for agricultural needs in arid regions.

The forest strips not only improved infiltration of precipitation but also reduced evaporation, helping to stabilise the water balance.

Soil biological activity before the introduction of agroforestry measures was extremely low and was 0.6-0.7, indicating a decrease in microbiological activity and degradation of the soil ecosystem. After the interventions, the values increased to 1.3-1.5, indicating a recovery of microbiological processes and improved soil health. These changes are attributable to the creation of multi-level forest strips, which promoted the development of soil microorganisms due to favourable conditions and enrichment with organic matter.

The overall analysis of the data showed that each of the three countries showed significant improvements in all the parameters studied. Successful implementation of agroforestry has reduced erosion, increased organic carbon content, reduced carbon dioxide emissions, increased soil water retention and restored biological activity. These results confirm the high effectiveness of agroforestry as a way to combat land degradation and restore ecosystem

functions. The improvements recorded in Ethiopia, Kenya and Malawi emphasise the importance of an integrated approach to natural resource management. The implementation of agroforestry practices has proven its ability to ensure the sustainable development of land ecosystems in the face of climate change and anthropogenic pressures.

Impacts of field-protected forest belts. Protective forest strips are essential for soil protection from erosion processes and the creation of sustainable agricultural ecosystems. A study identified that the use of such strips significantly reduces the intensity of water and wind erosion (Panagos *et al.*, 2021). Forest plantations slow down wind speeds, reducing the damaging effects on soils, and help retain surface water,

preventing washing away (R & Richard, 2022).

The analysis of the table above demonstrates a significant positive impact of agroforestry measures implemented in Ethiopia, Kenya and Malawi on key parameters of soil condition and water balance. Let's look at the changes in the main indicators. The intensity of water erosion before the introduction of forest belts ranged from 16 to 18 tonnes per hectare per year, which indicates high losses of fertile soil layer due to surface runoff. After the introduction of forest belts, this figure dropped to 5-7 tonnes per hectare per year, indicating a 60% reduction in erosion. This result was achieved by reducing the water flow rate, improving soil structure and preventing washout. Ethiopia, where initial erosion levels were highest, showed a particularly significant reduction (Table 2).

Table 2. Impacts of field-protected forest belts

Metric	Country	No forest belts	With forest belts	Effect of implementation
Water erosion intensity (tonnes/ha/year)	Ethiopia	18	7	A 60% reduction in surface runoff.
Wind erosion intensity (tonnes/ha/year)	Ethiopia	6	2	Reduced by more than half due to lower wind speeds.
Soil moisture (%)	Ethiopia	12	19	Increase by 30-40% due to reduced evaporation and improved structure.
Evaporation of moisture from the soil surface (mm)	Ethiopia	28	16	Reduced by 40% due to wind protection and microclimate creation.
Water balance (mm/m ²)	Ethiopia	110	150	Increase by 30% due to improved water retention capacity of the soil.
Water erosion intensity (tonnes/ha/year)	Kenya	16	6	A 60% reduction due to reduced surface runoff.
Wind erosion intensity (tonnes/ha/year)	Kenya	7	3	Reduced by more than half due to lower wind speeds.
Soil moisture (%)	Kenya	14	20	Increase by 30-40% due to reduced evaporation and improved structure.
Evaporation of moisture from the soil surface (mm)	Kenya	30	15	Reduced by 40% due to wind protection and microclimate creation.
Water balance (mm/m ²)	Kenya	115	158	Increase by 30% due to improved water retention capacity of the soil.
Water erosion intensity (tonnes/ha/year)	Malawi	17	5	A 60% reduction in surface runoff.
Wind erosion intensity (tonnes/ha/year)	Malawi	8	2	Reduced by more than half due to lower wind speeds.
Soil moisture (%)	Malawi	13	21	Increase by 30-40% due to reduced evaporation and improved structure.

Table 2, Continued

Metric	Country	No forest belts	With forest belts	Effect of implementation
Evaporation of moisture from the soil surface (mm)	Malawi	29	15	Reduced by 40% due to wind protection and microclimate creation.
Water balance (mm/m ²)	Malawi	112	160	Increase by 30% due to improved water retention capacity of the soil.

Source: compiled by the authors based on J. Kaluza (2023) and E. Nkansah-Dwamena (2023)

The intensity of wind erosion, which was at 6-8 tonnes per hectare per year before the introduction of the forest belts, has also been more than halved to 2-3 tonnes per hectare. This result reflects the importance of forest belts as a barrier that reduces wind speed and protects the soil from blowing away. This effect is particularly noticeable in arid areas such as Malawi, where wind erosion has been a significant problem.

Soil moisture increased by 30-40%, rising from 12-14% to 19-21% after the introduction of the forest belts. This improvement is attributed to reduced evaporation and increased soil moisture retention due to the shading provided by multi-level plantations. This effect was particularly pronounced in Kenya, where water balance has played a key role in ensuring sustainable agricultural production. Evaporation of moisture from the soil surface decreased by 40%, dropping from 28-30 mm to 15-16 mm. This decrease is due to the creation of a more favourable microclimate, where forest belts protect the soil from direct sunlight and winds. Ethiopia, which is severely affected by an arid climate, has demonstrated the greatest effectiveness in this regard (Handiso *et al.*, 2024).

The water balance, which reflects the soil's ability to retain moisture, improved by 30%, rising from 110-115 mm/m² to 150-160 mm/m². This improvement has significantly reduced the dependence of agricultural land on artificial irrigation and ensured stable production even in a changing climate. Particularly high growth was recorded in Malawi, where the use of forest belts minimised moisture loss.

Efficiency of agroforestry methods. The method of multilevel forest strips provided a multilateral impact on soil and the environment. A 40-70% reduction in wind speed helped to reduce wind erosion and preserve topsoil. In Ethiopia's Central Rift Valley, tiered forest belts with *Faidherbia albida* and *Acacia nilotica* species strengthened soil, reduced water runoff and protected against erosion. In Kenya, such strips, including *Grevillea robusta*, reduced soil temperatures by 2-5°C, increasing yields by 20-30% and increasing biodiversity by 150%. In Malawi, *Sesbania sesban* shrubs and grasses improved water-holding capacity by 30-40%, helping to restore pasture and protect soil from wind erosion. This was particularly relevant in Ethiopia and Kenya, where strong winds have traditionally exacerbated the problem of fertile layer loss. The plains of Kenya and Malawi showed improved microclimates by increasing soil moisture by 15-25%. The increase in moisture favoured crop growth conditions, allowing crops to adapt to periods of drought. A 2-5°C decrease in air temperature in the vicinity of forest belts was recorded in the drylands of Ethiopia. This effect reduced temperature stress in plants, which in turn increased productivity. Forest belts were critical in creating favourable conditions for agricultural activities in a region where high temperatures posed a serious threat to crop yields (Dobhal *et al.*, 2024).

Intercropping methods have proven effective in improving soil fertility and optimising resource use. In Malawi and Kenya, soil fertility was increased by 20-30% through enrichment

with organic carbon and nitrogen. This process reduced the dependence on mineral fertilisers, which was especially important in Ethiopia, where the restoration of the natural nutrient cycle reduced fertiliser costs by up to 50%. These changes emphasised the importance of a multi-level approach to agroecosystem management, where the combined use of trees, shrubs and herbaceous plants contributed to sustainable agricultural development (Naumova, 2024).

Crop yield increases of 15-25% were observed in Kenya and Malawi. This was possible due to improved soil structure and moisture retention properties. Forest strips protected the soil from evaporation and promoted even distribution of moisture, which increased water availability to plants. As a result, agricultural ecosystems in these countries have become more resilient to climate change and anthropo-

genic pressures. Spatial planning of forest strips reduced water erosion by 50-80% in Ethiopia and Kenya. This result was achieved through optimal spacing of strips, which prevented soil washing away and preserved soil fertility. The use of geographic information systems (GIS) in Kenya and Malawi increased the protected area by 30-40%. This ensured efficient use of land resources, especially in regions with intensive agricultural activities.

Increases in land use efficiency of up to 25% have been recorded in agricultural regions of Ethiopia and Kenya. Forest belts and intercropping technologies have played an important role in creating systems that optimally combine ecological and agricultural functions. This has contributed not only to the conservation of natural resources but also to increasing the economic returns from agricultural activities (Table 3).

Table 3. Effectiveness of agroforestry methods (2023)

Method	Metric	Results	Application examples
Multi-level forest belts	Reduced wind speed	40-70%, which reduced wind erosion and preserved the topsoil.	Ethiopia and Kenya are regions with intense wind erosion, where the strips have shown high efficiency.
	Increasing soil moisture	15-25%, improving the microclimate and conditions for crop growth.	Kenya and Malawi are flat regions with a favourable climate for improving the microclimate.
	Reduced air temperature in the vicinity of the strips	2-5°C, which reduces temperature stress in plants.	Ethiopia – regions with an arid climate, where lower temperatures have improved crop productivity.
Crop mixing technologies	Increase soil fertility	20-30% due to enrichment with organic carbon and nitrogen.	Malawi and Kenya are regions where soil fertility has increased due to organic processes.
	Reduced fertiliser requirements	Up to 50%, thanks to the restoration of the natural nutrient cycle.	Ethiopia – regions where restoring nutrient cycling has reduced fertiliser use.
	Increasing crop yields	15-25%, by improving soil structure and water retention properties.	Kenya, Malawi – there has been a significant improvement in the productivity of agricultural ecosystems.
Spatial planning	Reduced water erosion	50-80%, due to the optimal location of forest belts.	Ethiopia, Kenya – areas with high rates of water erosion, where the strips prevented soil washout.

Table 3, Continued

Method	Metric	Results	Application examples
Spatial planning	Increase the protected area	30-40%, through the use of geographic information systems.	Kenya and Malawi are regions where GIS analytics have been successfully used to optimise land resources.
	Improving the efficiency of land use	Up to 25%, due to an integrated approach to planning.	Ethiopia, Kenya – agricultural regions where forest belts have contributed to more efficient land use.

Source: compiled by the authors based on I. Vayansky & S.A. Kumar (2020), S. Koné & X. Galiegue (2023)

The overall analysis of the table shows that the introduction of agroforestry practices in Ethiopia, Kenya and Malawi has had a positive impact on soil health, agricultural productivity and ecosystem resilience. These changes highlighted the importance of an integrated approach to natural resource management. The results confirmed that agroforestry methods are an effective tool for restoring degraded land and adapting to climate change.

Increase biodiversity and stabilise the hydrological cycle. Figure 1 shows the distribution of two key parameters – biodiversity and soil water holding capacity – for Ethiopia, Kenya and Malawi in 2023. The visualisation was used to assess the contribution of each country to the overall environmental sustainability of the regions.

Biodiversity represented in terms of species was highest in Ethiopia, reflecting the country’s considerable ecosystem diversity. Kenya ranked second, with a moderate level of biodiversity, and Malawi was third with a slightly lower score. This distribution underlined the differences in natural conditions and the success of agroforestry measures aimed at restoring ecosystems. In terms of water-holding capacity, Ethiopia was also a leader, reaching the highest values among the three countries. Kenya was slightly behind but showed a steady increase due to measures to improve soil characteristics. Malawi, despite making a smaller contribution,

showed a marked improvement in water retention, which was particularly important for regions with an increased risk of drought.

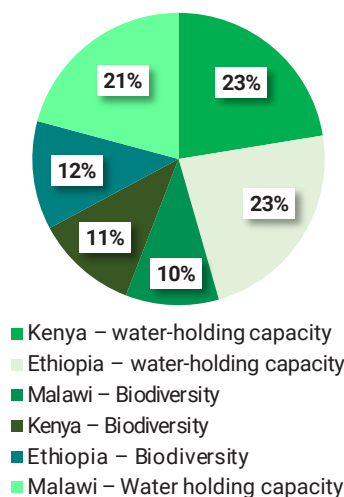


Figure 1. Increasing biodiversity and stabilising the hydrological cycle

Source: compiled by the authors based on Field studies (2024), S.N. Nakouwo & D. Zhang (2024)

Synergies between ecosystem characteristics, such as increased biodiversity and hydrological cycle restoration, in Ethiopia, Kenya and Malawi confirmed the effectiveness of agroforestry approaches and their long-term sustainability. These results indicated that agroforestry could be a systemic strategy for restoring ecological balance and maintaining land productivity. The simultaneous improvement of ecosystem functions highlighted the importance

of an integrated approach to natural resource management, where each measure reinforced the impact of the others. Forest belts and mixed plantations have created multi-layered ecosystems capable of performing a wide range of functions. In Ethiopia, these measures provided habitat for native plants and animals, including rare species, while in Kenya and Malawi, they improved the conditions for soil microorganisms. Tree and shrub plantations reduce temperatures, protect the soil from drying out and store organic carbon, which enriches the soil and increases the resilience of ecosystems to extreme climatic events, especially droughts.

The increase in biodiversity has restored complex ecosystem linkages that have strengthened long-term sustainability. In Kenya, pollinating insects have found favourable conditions, contributing to crop development. In Malawi, birds and small mammals have stabilised ecosystem processes by interacting with vegetation. These changes reduced the vulnerability of ecosystems to climate change, ensuring their adaptation to external influences. One of the key results was the restoration of the hydrological cycle. In Ethiopia, forest belts slowed down water runoff, increased rainfall infiltration and stabilised groundwater levels, reducing the risk of flooding and the impact of drought. In Kenya and Malawi, improved soil water-holding capacity has increased the availability of water for crops, reducing the need for artificial irrigation and water costs.

Air quality has also improved significantly. Forest belts in all three countries effectively absorbed carbon dioxide, reducing greenhouse gas emissions and contributing to the fight against global climate change. At the same time, trees and shrubs released oxygen, improving atmospheric conditions. Forest belts trapped dust and aerosol particles, which had a positive impact on the health of the local population and agricultural productivity.

The findings highlighted the need to scale up agroforestry activities in Ethiopia, Kenya and Malawi as a key tool for sustainable development. The implementation of these measures helped to restore degraded ecosystems, improve conditions for agriculture, improve the quality of life of the population and strengthen natural systems. These measures should form the basis for long-term planning in regions with high environmental and climate risk.

Discussion

The results of the study showed that agroforestry measures are a key method in improving the condition of degraded land, restoring ecosystem functions and increasing the resilience of agroecosystems. In countries such as Ethiopia, Kenya and Malawi, reductions in water erosion have reached 60-70% and wind erosion over 50%, highlighting the importance of forest belts and intercropping techniques for soil protection. These measures changed soil structure, including increased organic carbon and water holding capacity, strengthening the basis for sustainable agriculture. Restoring ecosystem connectivity has improved resilience to climate change and anthropogenic impacts. These results confirm that multi-level forest belts and mixed plantations are effective solutions for maintaining ecosystem stability (Floqi *et al.*, 2009; Skydan *et al.*, 2021).

Thus, the results demonstrate that agroforestry provides integrated restoration of natural processes, creating both ecological and economic benefits. J.M.S. Tomar *et al.* (2021) emphasised the role of agroforestry in combating soil degradation and mitigating climate change. J.M.S. Tomar *et al.* (2021) emphasise the importance of integrating agroforestry practices to improve the resilience of land systems and reduce water erosion. This study concurs with the finding of a 50-80% reduction in water erosion but adds a detailed analysis of spatial planning

to adapt forest strips to specific terrain conditions. In addition, J.M.S. Tomar *et al.* (2021), this study addressed the reduction in wind erosion and improving soil water-holding capacity, which enhances the overall understanding of agroforestry effectiveness.

R. Kaushal *et al.* (2021) addressed the benefits of agroforestry for soil and water conservation, emphasising the importance of forest plantations in slowing down erosion processes and improving soil structure. The results are consistent with these findings on the role of tiered forest belts in soil protection and fertility enhancement. However, this study provides a more detailed analysis of the methods of selecting trees, shrubs and herbaceous plants for the establishment of forest belts, concerning local climatic conditions. In addition, this study includes an analysis of the use of crop-mixing technologies to integrate ecological and agricultural functions, whereas the work of R. Kaushal *et al.* (2021) did not cover these aspects.

M. Jafari *et al.* (2022) emphasized on biological control of soil erosion using agroforestry technologies in arid regions. They emphasised the importance of forest plantations in improving soil resistance to water erosion. M. Jafari *et al.* (2022) included an integrated approach that considers both water and wind erosion as well as cumulative impacts on agricultural systems. In addition, the contribution of agroforestry to the restoration of ecosystem services such as the hydrological cycle and air quality improvement was considered, which is absent in the analysis of M. Jafari *et al.* (2022). This study complements their findings by showing that forest strips not only prevent erosion but also contribute to stabilising the water table and improving soil moisture. V.P. Gupta (2020) emphasises the role of agroforestry in soil protection and health improvement. The study emphasised reducing erosion losses and increasing soil organic carbon

content. This study also considers these aspects but extends the approach by analysing spatial planning and the use of crop-mixing technologies. For instance, this study shows that the introduction of tiered forest strips and mixed planting increases the organic carbon content by 20-30% and the water-holding capacity of the soil is increased by 80%. In contrast to the study by V.P. Gupta, this study covered the impact on biodiversity and restoration of ecosystem services such as hydrological cycle and air quality. S. Fahad *et al.* (2022) focused on the role of agroforestry systems in improving soil health, especially in the context of soil structure and nutrient content. The results of S. Fahad *et al.* (2022) were consistent with these findings of restoring soil fertility and reducing the need for mineral fertilisers. However, this study emphasised complementing these factors by improving water balance and increasing crop yields (up to 25%), which is not highlighted by S. Fahad *et al.* (2022). In addition, this study detailed methods of adapting agroforestry to local climatic and soil conditions, which expanded the application value.

X. Zhu *et al.* (2020) addressed the reduction of water, soil and nutrient losses and pesticide pollution reduction in agroforestry systems. Researches confirmed the importance of forest strips in preventing water erosion and nutrient retention. These results complemented these findings by showing a reduction in both water and wind erosion, as well as biodiversity restoration, which was not considered by X. Zhu *et al.* (2020). The inclusion of data on spatial planning and the use of mixed crops in this study demonstrates a more systematic approach, allowing both ecological and agrarian aspects to be considered. M.A. Marques *et al.* (2022) investigated the rehabilitation of degraded land and soil management using agroforestry systems. Scientists emphasised the importance of restoring soil structure and improving water

retention properties. This study also highlighted these aspects but added detailed analyses of spatial planning and plant species selection for different climatic zones. For instance, this study demonstrated an 80% increase in soil water-holding capacity and a role in reducing dependence on artificial irrigation, which was not highlighted in the work of M.A. Marques *et al.* (2022). The study by G. Sahoo *et al.* (2020) emphasised the use of agroforestry for the restoration of forest and landscape systems. The findings of S. Sahoo *et al.* (2020) on the role of forest strips in soil erosion protection concur with these findings. However, this study added analyses of mixed crops and multi-tiered strips to examine plant interactions at different ecosystem tiers. In addition, this study provides more detailed data on the 140% increase in biodiversity, demonstrating the integrated restoration of ecosystem functions, including the creation of new habitats. J.C. Dagar *et al.* (2020) investigated the use of agroforestry systems to restore degraded landscapes. They observed reduced erosion losses and improved soil structure, which was supported by these results. However, this study went further by showing not only effects on soil but also the restoration of the hydrological cycle, improvement of air quality, and reduction of greenhouse gas emissions. The implementation of geographic information systems for spatial planning considered in this study adds an applied aspect that is missing in the work of J.C. Dagar *et al.* (2020), S. Lebrazi & K. Fikri-Benbrahim (2022) highlights the importance of woody legume crops in improving soil health and increasing soil fertility. These results support these findings by showing an increase in organic carbon content by 20-30%. However, this study includes supplementing these findings by analysing crop mixing technologies that ensure the integration of legume plant functions with other crop types. This achieves not only improved soil structure,

but also a 50% reduction in fertiliser requirements, making the approach more sustainable.

The study by G. Jalilova *et al.* (2024) in four districts of South Issyk-Kul demonstrated that modern farmers are aware of the existing problems and their contribution to the decline in agricultural productivity and increased vulnerability to environmental change. An important problem of the absence of a mechanism for the exchange of agricultural knowledge between farmers was identified, as it is difficult for them to determine where and from whom to gain experience. It is proved that the integration of elements of agricultural consulting into the environment of farms has the potential to significantly stimulate the positive dynamics of agricultural development. The practical value of the research results is seen in the possibility of using them to mitigate the process of adaptation of agricultural production in developing countries to inevitable climate change. A comparison of the results shows that agroforestry is an effective tool for restoring degraded land, improving ecosystem functions and increasing the sustainability of agricultural systems. The main findings confirm a significant reduction in erosion losses, improved soil structure, increased fertility and restoration of the hydrological cycle. The study also emphasises the importance of forest belts and intercropping techniques for creating sustainable agricultural ecosystems.

A distinctive feature of this study is the integrated approach, including the adaptation of methods to different climatic conditions, the use of spatial planning and the analysis of biodiversity restoration. The results demonstrate the systemic impacts of agroforestry, covering both ecological and economic aspects. Thus, the study provides a broader picture of the impacts of agroforestry activities, rendering the data an important contribution to the development of sustainable land use and ecosystem restoration.

Conclusions

The study confirmed the high importance of agroforestry as an effective and comprehensive approach to restoring degraded land, increasing the resilience of agroecosystems and adapting to climate change. The study of methods such as shelterbelts, crop intercropping and spatial planning has identified specific examples of their effectiveness in different regions. The study found that the use of forest belts reduces water erosion by 60-70% and wind erosion by 50-60%. For instance, in Ethiopia, rainfall infiltration increased by 35%, which significantly reduced the risk of flooding. In Malawi, the water-holding capacity of the soil has improved by 30%, which has ensured sustainable agricultural development. These results demonstrate that forest belts not only stabilise the soil but also contribute to the accumulation of organic carbon, increasing soil fertility.

Crop mixing technologies have also shown this importance. For instance, in Kenya, the introduction of legumes into the rotation with cereals reduced the use of mineral fertilisers by 50%, improving the natural nitrogen cycle. In addition, mixed plantings in Malawi increased crop yields by 20-25%, which confirmed their economic and environmental benefits. Spatial planning was another key element of the study. The use of geographic information systems made

it possible to optimise the placement of forest belts, considering local natural and climatic conditions. As a result, in Ethiopia, forest belts on slopes prevented the formation of gullies, and in Malawi, their placement on flat areas ensured a uniform reduction in erosion processes.

Agroforestry has also proven effective in restoring ecosystem services. For example, in Kenya and Malawi, stabilising the hydrological cycle has led to improved water quality, reduced need for artificial irrigation and reduced risk of droughts. Forest belts have also helped to reduce dust and greenhouse gas concentrations, improving air quality and reducing climate impacts. These results highlight the versatility and adaptability of agroforestry technologies to different natural and climatic conditions. Not only do they improve soil quality and increase biodiversity, but they also ensure ecosystem resilience and agricultural productivity. The findings of the study highlight the need to scale up such measures and further study their impact to create even more effective approaches to natural resource management.

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Conflict of Interest

None.

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Вивчення методів і технік агролісомеліорації для запобігання ерозії ґрунтів на сільськогосподарських угіддях

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Анотація. Метою дослідження було виявлення ключових чинників і механізмів, що забезпечують підвищення стійкості ґрунтів та агроєкосистем через застосування агролісомеліоративних технологій в умовах мінливого клімату. Дослідження було зосереджене на впливі ползахисних лісових смуг, технологій змішування культур та методів просторового планування на відновлення деградованих земель і поліпшення екосистемних функцій. Методологія дослідження ґрунтувалася на узагальненні та аналізі даних з різних наукових джерел, а також на використанні теоретичних моделей і польових спостережень. Основна увага приділялася регіонам Ефіопії, Кенії та Малаві, де проводили аналіз впливу багаторівневих лісових смуг і змішаних культур на зниження ерозійних процесів, поліпшення структури ґрунту та відновлення біорізноманіття. Результати дослідження показали, що агролісомеліоративні заходи в цих країнах дали змогу значно знизити інтенсивність водної та вітрової ерозії, поліпшити водоутримувальну здатність ґрунту та відновити гідрологічний цикл. В Ефіопії лісові смуги сприяли підвищенню вологозапасу ґрунту в посушливих регіонах, у Кенії – поліпшенню врожайності сільськогосподарських культур за рахунок створення сприятливого мікроклімату, а в Малаві – захисту пасовищних екосистем від деградації. Ці заходи також сприяли збільшенню вмісту органічного вуглецю в ґрунті, що знизило потребу

в мінеральних добривах і мінімізувало антропогенний вплив на навколишнє середовище. Висновки підтверджують універсальність агролісомеліоративних підходів для відновлення земельних ресурсів та адаптації до кліматичних змін. Отримані результати демонструють значущість інтеграції агролісомеліоративних технологій у системи сталого управління природними ресурсами, що наголошує на необхідності масштабування в регіонах, схильних до деградації земель, зокрема в Киргизькій Республіці

Ключові слова: лісові насадження; просторове планування; екосистемні послуги; земельне відновлення; управління водним балансом; управління водним балансом

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Ecological aspects of climate change impact on tree species in forest ecosystems

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Abstract. The study aimed to assess how rising temperatures, changing precipitation patterns and increasing frequency of extreme weather events such as droughts, floods, and frosts affect forest ecosystems, and to identify possible consequences for their biodiversity and stability. This study encompassed a review of scientific literature, a comparative analysis of several climate

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change scenarios, and an evaluation of data about tree physiological processes, including photosynthesis, root development, and tree growth. The primary conclusions of the study indicated that climate change could exacerbate stressors for certain tree species, perhaps resulting in the substitution of these species with those that are more resilient or less dependent on specific climatic conditions. The results are important for predicting further changes in forest ecosystems and developing recommendations for their conservation. One of the key conclusions was the need to adapt forestry to new climate conditions, including the selection of climate-resistant tree species and the use of strategies to restore degraded forests. It is also relevant to improve the effectiveness of monitoring the state of forest ecosystems to respond to changes promptly and prevent the degradation of forest resources. Predicting possible climate change and analysing local conditions allowed for more effective planning of measures to conserve biodiversity and forest ecosystem services. Taking into account the data obtained, it is possible to create recommendations for sustainable forest management, which will help preserve their ecological and economic value in the face of climate change

Keywords: flora; biodiversity; environment; species vulnerability; vegetation

Introduction

Climate change represents a significant challenge of our era, impacting all ecosystems globally, including forests. Forests are essential for delivering ecosystem services, including carbon sequestration, water balance regulation, biodiversity conservation, and soil erosion prevention. Forests harbour almost 80% of terrestrial species and furnish resources for billions of individuals who rely on them to satisfy their needs (Huang *et al.*, 2024). Nevertheless, increasing temperatures, alterations in precipitation patterns, and the prevalence of extreme weather events provide a significant danger to the integrity of forest ecosystems. An elevation in average air temperature results in alterations in the photosynthetic activity of flora, potentially leading to a decline in arboreal growth and output. Under high temperatures, plants can show signs of stress, such as stomatal closure, which reduces carbon dioxide consumption and, consequently, reduces photosynthetic activity. Simultaneously, alterations in precipitation patterns result in droughts or, alternatively, heightened precipitation, so impacting

the hydrological regime in forests. This adversely affect the growth of tree root systems, as insufficient moisture may result in the mortality of young plants or diminish their capacity to respond to severe situations.

The occurrence of extreme weather events, including hurricanes, floods, wildfires, and frosts, can inflict physical harm on trees and lead to the devastation of forest stands. For example, climate change can facilitate the spread of new pests that are detrimental to forest health and can weaken forests' resilience to stress. A concerning element of climate change is its effect on the species makeup of forests. Changes in climate conditions may lead to the gradual displacement of certain tree species that are unable to adapt to new temperature and humidity conditions in favour of more resilient or invasive species (Skliar *et al.*, 2020).

Given these issues, it is essential to examine the adaptation mechanisms of forest ecosystems to climate change. Research focused on elucidating the physiological mechanisms of trees, their resilience and adaptive

capacity, and the formulation of appropriate forest management strategies in response to climate change is crucial for the preservation of these vital ecosystems in the future. Achieving sustainable development and forest conservation for future generations necessitates a thorough examination of the effects of climate change on forest ecosystems and associated ecosystem services.

J. Huang *et al.* (2024) investigated how photosynthetically active radiation affects the dynamics of sap flow at different stages of forest succession in subtropical forests. The authors noted that light intensity is a critical factor for tree growth, but questions remain about adaptation to climate change in different regions. The impact of altitude and slope exposure on carbon storage in Himalayan Forest soils was analysed by S. Kumar *et al.* (2024), focusing on the ecosystem processes that contributed to carbon storage in different landscape conditions and considering these aspects as a means of supporting natural climate change mechanisms. D. Srivastava (2024) focused on the biological aspects of climate-induced changes in ecosystems and offered practical recommendations for the adaptation of forest systems. A separate section was devoted to the ecosystem services of forests, their conservation, and their role in global environmental stability.

A. Sojitra *et al.* (2024) underscored the necessity of an interdisciplinary approach to forest research in relation to climate change, highlighting the importance of future research planning, while also indicating the ongoing requirement for practical recommendations for the conservation of certain forest types. The possibility of using controlled species migration to reduce the impact of climate change was considered by W. Xu & S. Prescott (2024). They noted the promise of this approach, but that it requires additional experimental evidence. J. Konic *et al.* (2024) evaluated the

contribution of imported trees to ecosystem services in Austrian woods. Despite the potential of introduced species, there are gaps in the study of their long-term impact on biodiversity.

Long-term changes in radial tree growth in mixed forests in China were investigated by X. Gong *et al.* (2024). The scientists analysed how climate change affected tree growth, in particular, whether these changes contributed to the spread of deciduous species. The study showed that changing climatic conditions could create more favourable conditions for deciduous species compared to conifers, which was important for predicting the future dynamics of these forests. S. Tampekis *et al.* (2024) presented the concept of planning and managing forestry operations using the principles of functional complex systems' science. The authors developed a systematic management method that considered the influence of multiple elements on the resilience of forest ecosystems and enabled forest adaptation to climate change. V. Kutskyi & I. Lakyda (2024) examined the influence of climatic variables on the distribution of this species, used modelling techniques to forecast future alterations in pine distribution. The work is aimed at improving conservation and management strategies for this species in changing ecological conditions. Finally, V. Kyyak *et al.* (2022) analysed the impact of climate change on habitats and proposed science-based methods for their conservation. In particular, they considered adaptive management strategies aimed at minimizing biodiversity loss and maintaining ecosystem resilience.

Despite significant focus on the effects of climate change on forests, numerous inquiries persist. The long-term effects on species composition and ecosystem services offered by forests remain little comprehended. There is a deficiency of generalized data regarding the adaptive potential of various tree species within a regional framework. This study aims to

evaluate the effects of climate change on arboreal growth and development, examine alterations in the species composition of forest ecosystems, and ascertain the implications of these changes for forest ecosystem services. The primary emphasis was on elucidating the methods by which trees adapt to fluctuating climatic circumstances, alongside formulating recommendations for the conservation and sustainable use of forest resources amid climate challenges.

Materials and Methods

Several theoretical methods were used to assess the impact of climate change on forest ecosystems, allowing for a comprehensive analysis and formulation of recommendations for the conservation of these ecosystems in the future. First, the analytical method was applied, which consisted of a thorough study of scientific literature and existing studies describing the impact of climate change on various aspects of forest ecosystems. This included the physiological processes of trees, alterations in forest species composition, and modifications in forest ecosystem functions, such as carbon sequestration, water circulation, and soil stabilization. The analytical strategy enabled to consolidate data from several research undertaken globally and locally, enhancing our comprehension of the possible effects of climate change on forest ecosystems.

As the study was of a theoretical nature, a significant part of the work was focused on systematizing and analysing the available data. This encompassed an examination of many papers detailing climate change and its effects on forests across diverse geographical areas. A review of studies examining alterations in temperature, precipitation, and extreme weather events and their effects on forest ecosystems was undertaken (Forzieri *et al.*, 2022; Seidl & Turner, 2022). This enabled the evaluation of

the resistance levels of various tree species to climate change and alterations in forest structure resulting from these causes. The findings from experimental studies by other researchers regarding the impact of climate change on the physiological processes of trees, encompassing photosynthesis, growth, and root system development, were also analysed, contributing to a more comprehensive understanding of the interaction between trees and climatic conditions, as well as their adaptive capacity to change (De Frenne *et al.*, 2021; Varol *et al.*, 2021).

The comparative analysis method enabled the comparison of several approaches to evaluating the effects of climate change on forest ecosystems, namely by contrasting different climate change scenarios, including alterations in temperature and humidity, and analysing their influence on diverse forest kinds. The comparison study facilitated the identification of forest ecosystems most susceptible to climate change and determined which tree species might adapt or extend their ranges.

The study was conducted in accordance with the ethical standards set out in the Convention on Biological Diversity (1992) and the Convention on International Trade in Endangered Species of Wild Fauna and Flora (1973). This guaranteed that the research adhered to international norms for the conservation of natural resources and biodiversity, assuring that the outcomes would not adversely affect ecosystems and endangered species.

Results and Discussion

The impact of climate change on tree growth and development

Climate change affects woody plants' key physiological processes, altering their growth, development, and resilience through interrelated factors like rising temperatures, shifting precipitation patterns, and more frequent extreme weather events that can amplify each other's impacts.

An elevation in mean annual temperatures alters the dynamics of photosynthesis, transpiration, and respiration in trees. For many tree species, optimal photosynthetic conditions depend on a certain temperature range. Increasing the temperature up to this range can increase the activity of photosynthetic enzymes, in particular rubisco, which leads to an increase in productivity. However, at temperatures above the optimum, enzyme activity decreases, and photosynthesis becomes less efficient, increasing the risk of heat stress. Heat stress also affects plant structures. In conifers, chloroplast damage is observed, which reduces carbon assimilation. In deciduous trees, tissue development processes are disrupted, and leaf expansion slows down. At the same time, the duration of the dormant period is reduced in many species, causing trees to enter the active growth phase prematurely, making them vulnerable to spring frosts. In regions with short winters, this cycle disruption can lead to yield losses and tree exhaustion (Allen *et al.*, 2010; Forzieri *et al.*, 2022).

Reduced precipitation in arid regions causes a chronic moisture deficit, which leads to a reduced water supply in the root system. This directly reduces transpiration and reduces the amount of nutrients reaching the leaves, disrupting photosynthesis. This is especially critical for young trees, whose root system is not yet sufficiently developed to access deep aquifer. In regions with excessive precipitation, the risk of soil flooding increases, which causes a lack of oxygen for the roots. Under anaerobic conditions, root decay is activated, which significantly weakens trees. In addition, constant

humidity creates favourable conditions for the development of fungal infections that can spread rapidly through the wood (Körner, 2021; Seidl & Turner, 2022).

Droughts significantly reduce transpiration, which leads to the drying of leaves and shoots. In the case of prolonged droughts, a tree can lose its secondary roots, which are responsible for water absorption, making it more vulnerable to other stress factors. Frosts are particularly dangerous for young shoots and flowers, which often develop after the shortened winter period. Even short-term exposure to low temperatures can cause damage to cell membranes, leading to tissue necrosis (Natalchuk & Rudnyk-Ivashchenko, 2024). In colder regions, this can reduce tree survival, reduce productivity and even cause death. Floods, in turn, damage the root system, cause soil erosion and create unfavourable conditions for rooting. The result is a decrease in the resilience of forests to windstorms and damage to the mechanical structure of trees.

Warming creates favourable conditions for many insects, such as bark beetles or sawflies, which reproduce and spread faster (Shahini *et al.*, 2024). New warm regions become available for invasive species that were previously restricted to cold temperatures. Increased humidity favours the development of fungal diseases, such as fusarium or rust, which attack leaves, branches, and wood (Table 1). Affected trees often have reduced vigour and become more vulnerable to other stress factors. At the same time, some diseases that were previously considered insignificant can become epidemic due to changes in environmental conditions.

Table 1. Impact of climatic factors on physiological processes of trees and their consequences

The climate factor	Physiological effects	Consequences for trees
Increase in temperature	Disruption of photosynthesis, reduction of dormancy	Exhaustion, heat stress, risk of frost
Precipitation deficit	Water stress, reduced transpiration	Reduced growth, root death

Table 1, Continued

The climate factor	Physiological effects	Consequences for trees
Excessive rainfall	Flooding of the root system	Root rot, fungal infections
Frequent droughts	Disruption of the water balance	Leaves drying out, trees dying
Frosts	Tissue necrosis	Reduced productivity, damage to young shoots
Spread of pests	Invasions of new species	Damage to wood, reduction of biodiversity
Fungal diseases	Damage to leaves, branches, wood	Reduced viability, slower growth

Source: C.D. Allen *et al.* (2010), C. Körner (2021)

To formulate successful methods for adapting forest ecosystems to climate change, it is essential to consider the ecological traits of various tree species, their resilience to water scarcity, excessive moisture, thermal stress, and biotic influences. Trees with high resistance to flooding, such as white willow (*Salix alba*), black poplar (*Populus nigra*) and aspen (*Populus tremula*), are well suited to high humidity. For example, in regions with frequent flooding, these species demonstrate stable viability due to their ability to form adventitious roots and anaerobic respiration. However, even these species require adaptation measures such as soil reclamation to reduce the duration of water stagnation.

Pine (*Pinus sylvestris*), oak (*Quercus robur*) and juniper (*Juniperus communis*) are well suited to regions with low rainfall. These species demonstrate the ability to conserve water due to their smaller leaf blade, waxy coating on needles or leaves, and strong root systems that reach deep aquifers. In countries with Mediterranean climates, the olive tree (*Olea europaea*) has successfully adapted to extreme droughts through stomatal transpiration regulation mechanisms (Shahini *et al.*, 2009; Ninemets, 2010).

The duration of adaptation to climate change varies for different species. For example, Scots pine shows the first signs of adaptation to rising temperatures in 10-15 years, which is reflected in changes in the chemical composition of wood and the structure of the

root system. Common oak takes about 20-30 years to fully adapt to lower precipitation due to the formation of deeper roots. Moisture-loving species such as poplar or willow adapt more slowly, as their adaptation mechanisms are limited to physiological processes without significant changes in tissue structure (Intergovernmental Panel on Climate Change, 2021).

Enhancing the resilience of forest ecosystems necessitates the integration of biological, engineering, and management strategies. Selecting species that combine high levels of productivity with adaptive resilience is a key step. For example, in drought conditions, the use of lodgepole pine hybrids with resistance to water deficit can be an effective solution. In humid regions, it is advisable to implement drainage and mulching systems to maintain a stable level of soil moisture. Adapting forests to climate change is a protracted endeavour necessitating continuous ecosystem monitoring and the implementation of innovative management strategies aimed at conserving natural resources and biodiversity.

Changes in the species composition of forest ecosystems

Climate change is altering forest ecosystems' species composition by transforming the growing conditions for various tree species. Through rising temperatures, altered precipitation patterns, and more frequent extreme weather events like droughts, frosts, and floods, it's

reshaping competitive dynamics between species while affecting their geographic distribution and survival rates. Cold-loving tree species, such as spruce, white fir and larch, are the most vulnerable to warming. They traditionally grow in cold climates and have a limited ability to adapt to higher temperatures. As temperatures rise, their ranges shift northwards or upwards to higher mountainous areas. This leads to a decline in their numbers in their usual territories, where the climate is no longer optimal for their growth. At the same time, warmer climatic conditions are contributing to the expansion of the ranges of warmth-loving species, such as fluffy oak, Scots pine and other species that can withstand higher temperatures and less humid conditions. These species are actively developing new ecological niches in regions that are becoming warmer, which can change the balance between different types of forests. Climate change also has a significant impact on moisture-loving trees. Rising temperatures combined with insufficient moisture are leading to a decline in species such as common oak, linden, or alder. These species require stable moisture for normal growth, and water shortages are becoming a serious problem for their survival. Alterations in the quantity and distribution of precipitation result in modifications to forest structure, as moisture-dependent plants are progressively supplanted by more drought-tolerant species like oak or pine (De Frenne *et al.*, 2021; Varol *et al.*, 2021).

At the same time, climate change creates favourable conditions for invasive tree species. For example, Gleditsia or Amorpha bush, which are highly adaptable to environmental

changes, can expand their ranges to new regions, occupying vacant ecological niches. They are able to quickly develop new territories and often displace native species, which leads to a decrease in biodiversity and disruption of natural ecological links in forests. Climate change affects the structure of forest communities, changing not only the composition of species but also the physiological characteristics of forest ecosystems. For example, in regions where temperatures are rising, coniferous forests may gradually change to mixed or deciduous forests, reducing the overall density of forest cover and changing the nature of the undergrowth and reducing soil fertility. These changes not only affect the aesthetic appearance of forests but also impair crucial ecosystem functions like water purification, moisture retention, and soil conservation, while climate change further threatens vulnerable species such as conifers, reducing their ability to perform vital ecological services including carbon sequestration and erosion protection. At the same time, replacing these species with more heat- and drought-tolerant species may help maintain some ecosystem functions, but reduce overall forest biodiversity (Peñuelas & Boada, 2003).

In general, climate change affects the species composition of forest ecosystems through complex interactions between temperature, precipitation, moisture, and competition between species. These changes can lead to significant structural changes in forests, as well as the loss of some ecological functions, such as biodiversity stability and water regulation. Table 2 illustrates the responses of various tree species to climate change.

Table 2. Effects of climate change on the species composition of forest ecosystems and its repercussions

Type of changes	Examples of species that respond	Consequences
Warming	Spruce, fir, larch	Range reduction, migration to mountainous areas or north
Moisture deficiency	Common oak, linden, alder	Loss of productivity, degradation of ecosystems

Table 2, Continued

Type of changes	Examples of species that respond	Consequences
Expanding our habitats	Fluffy oak, Scots pine	Replacement of cold-loving species, expansion to warmer regions
Infestation	Gleditsia, Amorpha	Displacement of native species, reduction of natural diversity
Structural changes	Deciduous forests instead of conifers	Reduction of density, change in functional characteristics of ecosystems

Source: J. Peñuelas & M. Boada (2003), D.M. Richardson & M. Rejmánek (2011)

Changing forest species composition affects the economy by reducing resource availability, changing forest productivity and increasing management costs. For example, the shrinking ranges of cold-loving species such as spruce and fir reduce the amount of valuable timber used in construction and furniture production. At the same time, the expansion of warmth-loving species, such as fluffy oak, is changing the structure of raw materials, which requires the woodworking industry to adapt. The moisture deficit, which leads to a loss of productivity in species such as linden and alder, affects forestry, which depends on a stable supply of resources.

Invasive species, such as *Gleditsia*, create additional costs for their control, which increase as they spread. The lack of adaptation to local climatic conditions and the poor quality of their wood limits their economic value, while threatening to lose natural forest resources.

Invasive species management strategies include several approaches aimed at reducing their negative impact on forest ecosystems. Early detection and monitoring are key measures that allow localizing new areas of invasive species using modern technologies such as remote sensing and GIS systems. Physical removal of young trees of invasive species, combined with planting of native resistant species, helps to preserve natural biodiversity. Simultaneously, the implementation of biological control strategies, including the utilization of natural predators of invasive species,

aids in diminishing their populations without adversely affecting ecosystems. Encouraging the planting of native tree species adapted to climate change ensures their superiority over invasive species. This measure is important for creating sustainable forest plantations. Raising environmental awareness and informing local communities about the negative effects of invasive species is paramount. The integrated application of these strategies contributes to the adaptation of forest ecosystems to climate change, while maintaining their ecological stability and economic value.

Ecosystem services of forests in the context of climate change

Forests are one of the key components of the global ecosystem, performing numerous functions that maintain ecological balance. Some of the most important functions of forests include carbon sequestration, water cycle regulation, soil erosion protection, biodiversity maintenance, water filtration and ensuring the stability of local climatic conditions. All these processes are being seriously disrupted, which affects not only the condition of the forests themselves, but also human well-being. The ability of forests to absorb carbon dioxide, which is the main greenhouse gas, is critical to slowing global warming. This process depends on the level of photosynthetic activity of trees, their growth, and biomass accumulation. Climate change, such as rising average annual temperatures and frequent droughts,

significantly reduces the efficiency of photosynthesis, especially in moisture-loving species such as fir, beech, or oak. As a result, trees grow more slowly, which reduces the amount of carbon that is sequestered and retained in forests. Moreover, catastrophic weather phenomena, including wildfires and hurricanes, facilitate the swift release of carbon sequestered in wood, transforming forests from natural carbon sinks into sources of carbon dioxide.

The root systems of trees play a key role in retaining moisture in the soil, preventing it from evaporating and running off quickly during storms. In arid conditions, trees, especially those with shallow root systems such as alder or aspen, are unable to maintain the required level of soil moisture. This leads to the depletion of aquifers and increased droughts, which negatively affects both local ecosystems and agriculture. Erosion protection and soil stabilization are important functions of forests, especially in mountainous and sloping areas. Climate change, which is leading to more extreme precipitation events and increased intensity of storms, is exacerbating erosion processes. In areas where forest cover is degraded due to drought or felling, soil becomes more vulnerable to leaching. This not only reduces soil

fertility, but also leads to flooding in low-lying areas due to the accumulation of sediment in water bodies (Abbass *et al.*, 2022).

The water filtration capacity of forests relies on the diversity of tree species and their efficacy in purifying water from detrimental contaminants. Under climate change, the risk of losing this mechanism increases as species diversity decreases, and invasive plants spread. Monocultures, which are often created for reforestation, have a limited ability to filter water because their root system does not provide sufficient interaction with soil microorganisms that are involved in natural water purification. Maintaining the biodiversity of forests is the basis of their ecological sustainability, but this process is also under threat. Climate change is disrupting the ecological balance, contributing to the displacement of some species by others that are less vulnerable to changing conditions (Ismayilzada *et al.*, 2023). For example, the spread of invasive species such as *Gleditsia* or *Amorpha* often leads to the displacement of native species such as linden or maple (Table 3). This disrupts the complex ecological relationships that maintain the stability of forest ecosystems, including interactions between trees, pollinating insects, birds and other organisms.

Table 3. Ecosystem services of forests and their disruption under climate change

Ecosystem service	Disruption due to climate change	Environmental impacts
Carbon sequestration	Reduced photosynthesis, emissions from fires	Increasing CO ₂ levels in the atmosphere, increasing the greenhouse effect
Regulation of the water cycle	Moisture deficit, reduced water retention	Deteriorating access to water, increasing frequency of droughts
Erosion protection	Loss of forest cover, increased surface run-off	Soil destruction, increased flood risk
Water filtration	Decrease in tree diversity, spread of monocultures	Accumulation of harmful substances in aquifers
Supporting biodiversity	Displacement of native species, loss of interconnections between organisms	Reduced ecological sustainability of forests, disruption of ecosystem functionality

Source: K. Abbas *et al.* (2022), A. Łubek *et al.* (2021)

To preserve the ecosystem services of forests in the context of climate change, it is necessary to implement adaptation measures, such as enriching forests with resilient tree species, creating conservation corridors and managing water resources. At the same time, it is important to reduce anthropogenic pressure on forests, in particular by reducing illegal logging and promoting natural forest regeneration.

Climate change poses unprecedented challenges for forest conservation, demanding both proactive management and flexible adaptation strategies. A critical focus lies in preparing forest plantations for shifting climate patterns through careful tree species selection. Foresters must identify varieties capable of thriving under higher temperatures and water scarcity. This often means leveraging native species already adapted to changing conditions while thoughtfully introducing hardy newcomers that can weather future climate shifts. Biodiversity plays a vital role in maintaining healthy forests – the more diverse an ecosystem, the better it can withstand environmental pressures. Building climate resilience requires transitioning away from monocultures toward mixed-species and natural forest systems that better mirror nature's complexity. Mixing tree species and incorporating natural plant communities reduces the risks of diseases and pests, which are a serious threat to monotonous forests.

The creation of nature conservation corridors is also an important element of adaptation. Thanks to such corridors, plant and animal populations can be maintained and preserved, which contributes to the conservation of biodiversity. Water management is another critical aspect. The introduction of technologies that promote water conservation, such as irrigation and protection against surface run-off, can increase the efficiency of water use in forest ecosystems. Additionally, establishing a rainwater harvesting system can help maintain soil

moisture levels during dry periods. Conservation and restoration of degraded forests is an important area of adaptation. This can include measures to restore natural ecosystems, such as reforestation areas that have lost cover and supporting natural regeneration processes. The education and engagement of local communities in forest management activities are crucial components of adaptation. Enhancing public knowledge on the significance of forests and their ecological role fosters the development of local conservation projects. Community participation in forest restoration programmes can ensure their sustainability and long-term results.

Protecting and restoring the ecosystem functions of forests is also an important aspect. Forests perform numerous ecological functions, such as carbon sequestration, water balance regulation and protection against soil erosion. Monitoring climate change and the state of forest ecosystems is equally important. Regular monitoring facilitates the timely identification of alterations, including increasing temperatures, variations in precipitation, and the advent of novel pests or illnesses, so enabling a swift reaction to these developments. This will make it possible to make the necessary management decisions based on scientific data and predict possible changes in the future.

Reducing greenhouse gas emissions is another important area. Proactive measures to mitigate emissions will aid in decelerating climate change and alleviating its adverse effects on forest ecosystems. Forests are crucial for sustaining the carbon balance as carbon reservoirs; thus, their protection and regeneration are vital for addressing climate change (Huseynli *et al.*, 2024). Education and public engagement significantly contribute to forest conservation. Enhancing knowledge of the significance of forests and their contribution to combating climate change fosters community initiatives for forest conservation and

participation in replanting efforts. The engagement of local communities in the preservation of forest ecosystems guarantees their sustainability and enduring outcomes. The development of adaptation strategies for forestry and agriculture will help avoid conflicts between the use of forest resources and ecosystem conservation. This entails a sustainable methodology for utilizing forest resources that preserves the ecological functions of forests and sustains their resilience to climate change. Taking these factors into account will allow forest ecosystems to maintain their functions even in the future, contributing to the stability of ecological processes on the planet.

A reduction in trees' capacity to sequester carbon results in heightened greenhouse gas concentrations in the atmosphere, hence exacerbating global warming. This therefore influences climatic conditions, augmenting the frequency and severity of extreme meteorological phenomena, including hurricanes, floods, and droughts. This results in increased costs for infrastructure restoration, as well as increased costs for adaptation to new climate conditions. Secondly, the decline in water quality due to the loss of forests has a negative impact on public health. Forests perform an important function of water filtration, and their degradation leads to water pollution. This can cause an increase in the incidence of diseases among the population, which, in turn, creates additional financial burdens on the healthcare system.

Social impacts also include reduced resources for local communities that depend on forests for their livelihoods. Many people, especially in rural areas, rely on forests for timber, medicinal plants, food, and even income from ecotourism. The loss of these resources can lead to lower living standards, increased poverty and social tensions in these communities. The disappearance of species that play an important role in agroecosystems can lead to lower crop

yields and, as a result, food shortages. This may trigger social conflicts due to competition for limited resources. Thus, the economic and social consequences of the loss of forest ecosystem services are complex and multifaceted, requiring urgent response and implementation of measures to conserve and restore them.

A. Łubek *et al.* (2021) analysed the impact of climate change on the functional diversity of ecosystems, in particular on the distribution of lichens, which are indicators of ecological condition. The results of the study showed that invasive tree species, such as *Gleditsia*, are displacing native species, which has a negative impact on biodiversity. The authors also noted that such changes contribute to the imbalance of ecosystems, creating new challenges for forest management.

The importance of modelling future forest change scenarios was highlighted by J. Huang *et al.* (2021), who used virtual reality data to predict climate impacts on forests. This is consistent with the study's findings on the need to develop adaptation strategies for forestry. L. Suz *et al.* (2021) emphasized the critical role of mycorrhiza in the adaptation of trees to stressful conditions, in particular under conditions of moisture deficit. The study confirmed that changes in the precipitation regime negatively affect the ability of trees to maintain water balance, which reduces the efficiency of forests in performing key ecosystem functions. Similar results were reported by L. Nunes *et al.* (2021), who analysed the impact of climate change on forests in the Mediterranean region and highlighted the need for adaptation measures to stabilize these functions.

The research indicated that increasing temperatures induce alterations in the photosynthetic mechanisms of trees, particularly conifers, which possess a restricted capacity to acclimate to thermal stress. N. Naudiyal *et al.* (2021) noted that species such as *Abies* and

Picea are particularly vulnerable to warming, which changes their potential distribution range. Y.-S. Wang & J.-D. Gu (2021) investigated the adaptation mechanisms of mangrove ecosystems to heat and moisture stress. This indicates the universality of mechanisms that may be common to different types of ecosystems.

S. Bandh *et al.* (2021) analysed the spread of invasive species in the context of climate change and noted that this can reduce the functionality of local ecosystems. The results showing changes in the photosynthetic activity of trees and their adaptive mechanisms to water stress are in line with the findings of Y. Liu *et al.* (2020), who emphasized the importance of mycorrhiza in ensuring nutrient metabolism under climate change. P. Baldrian *et al.* (2023) emphasized that the forest microbiome is essential for the resilience of tree species to climate change, corroborating findings on the interaction between root systems and soil bacteria.

The findings on the replacement of less resilient tree species with more adapted ones are confirmed by X. Morin *et al.* (2021), which highlights changes in the species structure of tree communities through succession models. They pointed out that a decline in the number of certain species can have negative consequences for forest stability. The result indicates a necessity for additional investigation into the relationship between tree species and microbial populations to enhance the adaptive potential of forests. The study's findings, which reveal a decline in forests' capacity to control the water cycle, align with the analysis conducted by F. Orsi *et al.* (2020), who noted the loss of essential ecosystem services resulting from forest degradation in Europe.

A. Ali (2023) emphasized the importance of an integrative approach to preserve forest ecosystem services in the face of global change. The results obtained on the degradation of

certain tree species under the influence of changes in temperature and precipitation are confirmed by the findings of J. Blanco & Y. Lo (2023). The identified changes in species composition and adaptive capacity of tree species correlate with their recommendations on the need to apply integrated methods to predict the consequences. The study also found a decrease in the carbon sequestration capacity of forests due to loss of productivity and tree degradation. This is in line with the findings of the scientists, who emphasized that new modelling approaches can improve the accuracy of assessing changes in forest ecosystem functions under climate change.

The results on the reduction of cold-loving species' ranges and the expansion of warm-loving and invasive species are in line with the findings of S. Chivulescu *et al.* (2023). Their study noted that maintaining forest resilience is key to ensuring ecological balance, particularly in the face of climate change, as observed in the peri-urban forests of Romania. The data obtained confirm the importance of implementing adaptation measures, in particular through maintaining biodiversity and preserving the resilience of forests. The researchers noted that the transition to mixed forests and the integration of protected areas into the management structure can significantly increase climate change resilience. Studies on the increased spread of tree pests and diseases under the influence of climate change are consistent with the findings of J. Guegan *et al.* (2023). They highlighted that climate change facilitates the proliferation of novel pests and pathogens that endanger the stability of forest ecosystems.

The findings validated the intricate and multifaceted influence of climate change on forest ecosystems. Consistency with international research highlights the global importance of adaptation strategies for maintaining forest stability and functionality. This work

enhances the comprehension of forest processes and can provide a foundation for formulating successful forest ecosystem management strategies.

Conclusions

The research established that climate change, characterized by elevated temperatures, altered precipitation patterns, and a rise in extreme weather occurrences, significantly affects forest ecosystems, including tree physiological processes, species composition, and ecosystem functioning. Variations in temperature and humidity directly influence the growth and development of trees, modifying their capacity for photosynthesis, growth, and root system formation. As a result, some tree species may be vulnerable to changes, leading to their replacement by more resilient species or to a reduction in the number of trees of certain species.

Modifications in forest species composition, particularly the displacement of tree species, are increasingly influencing the capacity of forests to fulfill their ecological roles, such as carbon sequestration, water regulation, erosion mitigation, and soil stabilization. Disruption of these functions can have serious consequences for climate, agriculture and water resources, in particular by reducing the ability of forests to absorb carbon dioxide and maintain water flow in ecosystems. A comparative investigation of various climate change scenarios indicates that forest ecosystems exhibiting high biodiversity are more tolerant to the adverse impacts of climate change. Consequently, conserving and restoring biodiversity is essential for the response of forests to climate change. Specifically, altering forest structures and substituting non-adapted species with more climate-resilient varieties can be a crucial measure in safeguarding forest ecosystems for the future.

It has been proven that adapting forestry to new conditions is a crucial undertaking in the context of climate change. It is essential to formulate and execute forest management methods that would aid in preserving their ecological functions and stability. This encompasses the selection of climate-resilient tree species capable of enduring elevated temperatures, altered precipitation patterns, and other harsh weather phenomena. To preserve the ecosystem services of forests, methods should be used to restore degraded forests and prevent the degradation of forest land. Given the identified trends and changes, there is a growing need for regular monitoring of forest ecosystems.

Despite the importance of the results, the study has several limitations. One of the main ones is the lack of accurate experimental data on changes in forest ecosystems as a result of climate change. The theoretical nature of the study limits the ability to accurately predict the impact of changes on specific forest areas, as different regions may respond differently to climate change. It should also be borne in mind that factors not directly related to climate, such as anthropogenic pressure, can have a significant impact on the state of forest ecosystems. Further study should focus on creating more precise models to forecast the effects of climate change on forest ecosystems, including local variables. This involves examining the adaptive strategies of tree species in response to climate change and formulating techniques for the conservation and restoration of forest ecosystems threatened by global climate change.

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Conflict of Interest

None.

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Екологічні аспекти впливу кліматичних змін на деревні види в лісових екосистемах

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Анотація. Метою дослідження було оцінити, як підвищення температури, зміна режиму опадів та збільшення частоти екстремальних погодних явищ, таких як посухи, повені та

заморозки, впливають на стан лісових екосистем, а також визначити можливі наслідки для їх біорізноманіття та стабільності. Дослідження включало аналіз наукової літератури, компаративний аналіз різних сценаріїв кліматичних змін, а також оцінку наявних даних про фізіологічні процеси дерев, таких як фотосинтез, розвиток кореневої системи та зростання дерев. Основними результатами дослідження стали висновки про те, що зміни клімату можуть сприяти посиленню стресових факторів для деяких видів дерев, що в свою чергу може призвести до заміни деревних видів більш стійкими або менш вимогливими до кліматичних умов. Отримані результати мають важливе значення для прогнозування подальших змін у лісових екосистемах та розробки рекомендацій для їх збереження. Одним з ключових висновків була необхідність адаптації лісового господарства до нових кліматичних умов, що включає вибір стійких до змін клімату видів дерев, а також використання стратегій для відновлення деградованих лісів. Також важливо підвищити ефективність моніторингу стану лісових екосистем для своєчасного реагування на зміни та запобігання деградації лісових ресурсів. Прогнозування можливих змін у кліматі й аналіз локальних умов дозволило ефективніше планувати заходи щодо збереження біорізноманіття та екосистемних послуг лісів. Враховуючи отримані дані, можна створити рекомендації для стійкого управління лісами, що сприятиме збереженню їх екологічної та економічної цінності в умовах змін клімату

Ключові слова: флора; біорізноманіття; навколишнє середовище; вразливість видів; рослинність

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Improving propagation technology of *Ligustrum L.* planting material for greening urbanised areas

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Abstract. The relevance of the study is due to the need to improve the quality of planting material and expand the range of ornamental plants for landscaping urbanised areas. The aim of the study was to improve the technology of privet propagation, taking into account the biological characteristics and factors affecting the rooting process, such as the use of root formation stimulants and the choice of substrates. Comparison of rooting of green and lignified cuttings revealed different efficiency depending on the substrates and root formation stimulants used, in particular, Rizopon, Heteroauxin super and Grandis. The experiments showed that the most effective root stimulant was Rizopon, which increased the percentage of rooting of cuttings by 5-10% compared to the control. The highest rooting rates were observed in *Ligustrum vulgare* L. and its cultivars 'Atrovirens' and 'Aurea', reaching 96 %. The substrate based on peat and river sand (2:1) was the most optimal for most species, while for *Ligustrum ibota* 'Musli' the use of pure river sand was more effective. The results of propagation by lignified cuttings showed an order of magnitude higher percentage of rooting for most of the studied plants, in particular, *L. vulgare* L., and its cultivars, the percentage of rooting ranges from 86-96%, while rooting by green cuttings – from 85-90%. In the case of *L. ovalifolium* Hassk. These indicators were somewhat lower but satisfactory, lignified cuttings 75-92%, green cuttings 74-90%. *L. ibota* 'Musli' and *Ligustrum japonicum* 'Green Century' have mediocre rooting results both with lignified and green cuttings, *L. ibota* 'Musli' when propagated by lignified cuttings had a result in the range of 12-14%, and lignified cuttings 66-68%. *L. japonicum* 'Green Century' had a higher percentage of rooting when propagated by lignified cuttings 47-62%. The results of the study can be used to increase the efficiency of privet propagation and improve the technology of growing high-quality planting material resistant to the conditions of the urbanised environment. These studies serve as an informational scientific basis for improving the systems of ornamental seedling production

Keywords: ornamental nursery; vegetative propagation; green plantings; substrate; rootability; urban environment; morphometric indicators

Introduction

Plants play an important role in creating a comfortable and healthy climate in urban landscapes. In general, they have a positive effect on both the psycho-emotional state of a person and air quality, reducing the level of pollution and preserving the ecological integrity of urban ecolandscapes. When planning urban green spaces at the macro and regional levels, it is extremely important to study plant species of urban green spaces and introduce new species taking into account climatic conditions environmental pollution.

J.C. Fisher *et al.* (2022) described the importance of plants in urban environments, demonstrating that an increase in the number of

flowering plants in cities positively affects people's mental wellbeing, highlighting the role of urban biodiversity in enhancing the quality of life in cities. This is complemented by the research of S. Ghafari *et al.* (2020) and T. Blanusa *et al.* (2019), who assess plant species for urban green spaces. They emphasized the importance of selecting appropriate plant species, particularly for hedges, that contribute to urban biodiversity and the well-being of residents. O. Strashok (2022) also examined the significant role of urban plants in shaping the microclimate of modern cities, along with their recreational and aesthetic functions. The study highlighted the impact of climate change and

temperature variability on plant growth and development, focusing on the adaptive potential of plants in the urban environment, particularly in Kyiv.

An important element of urban green spaces is privet (*Ligustrum*). This is determined not only by its aesthetic qualities but also by its ability to adapt to various growing conditions, including care practices, as noted by H.B. Lukashchuk (2020). S.I. Kuznetsov *et al.* (2020) and J. Dong *et al.* (2021) described common privet as a highly winter- and drought-resistant plant, undemanding to soil, tolerating slight soil salinity, and thriving well in urban environments, particularly in conditions of air pollution. Special attention is given to its resistance to dust and gas, as highlighted by T. Tkachenko *et al.* (2023). With the increasing popularity of this plant, there is a need to provide high-quality planting material.

As stated by V.M. Maurer (2019), to obtain uniform seedlings, including privet (*Ligustrum*), the vegetative propagation method was most often used, namely, cuttings, since it allowed to preserve the genetic features of the mother plant and obtain material that corresponds to the specified characteristics, for example, the colour of the leaves, or crown shape. However, the propagation process requires the improvement of scientific and agrotechnical methods to improve the quality and efficiency of growing privet (*Ligustrum*) planting material and its cultivars.

The study of factors affecting the root-forming ability of shoots and the subsequent growth of these plants is a key aspect for improving cultivation technology. As noted by E. Kentelky *et al.* (2021), biological features of the taxon, parameters of the physiological state of plants, rooting conditions and the use of various drugs can affect the reproduction process. In particular, E.M. Badawy *et al.* (2020) in their study described the process of reproduction of *Ligustrum ovalifolium* L., where the main

emphasis was placed on the timing of cutting material harvesting, as well as the effect of auxins on the quantity and quality of root formation. P. Basuchaudhuri (2021) researched the effect of auxins on the rooting ability of the cutting material, in particular, the most popular and most reliable hormone for rooting is IBA – indolylbutyric acid, although NAA – naphthylacetic acid was also used. H. Chen *et al.* (2023) investigated the effect of different concentrations of indole-3-acetic acid (IAA), indole-3-butyric acid (IBA) and indene-naphthaleneacetic acid (ABT-1) on rooting and dynamic changes in endogenous hormone content in cuttings. Additionally, I. Karakaş & B. İzci (2024) explored the application of auxins (IBA 2000 ppm and NAA 1000 ppm) for the rooting of lavender cuttings. In turn, K. Chinnasamy *et al.* (2024) analysed the effects of auxin at various concentrations, specifically IBA and NAA (1000, 2000, 3000, 4000, and 5000 ppm), on the rooting of *Morus indica* L. cuttings. The effect of auxins on the rooting of cuttings was also investigated by V.R. Fursa & A.P. Pinchuk (2024), in particular the use of the following stimulants was described: Rhizopon AA (1%) (powder, 3-indolylbutyric acid (IBA), 1-Naphthylacetic acid (NOA) and 3-Indoleacetic acid (IC)), succinic acid and potassium humate. Certain aspects of the technology of growing privet (*Ligustrum*), in particular *Ligustrum ovalifolium*, *Ligustrum ibota* and *Ligustrum japonicum*, remain under studied by researchers and require a deeper study.

The aim of this study was to improve the technology for cultivating planting material that preserves the ornamental traits of the parent privet (*Ligustrum*) plants and their cultivars, taking into account all aspects of their biological characteristics and factors affecting propagation. To achieve this goal, the following tasks were outlined: to assess the reproductive capacity of cuttings and to develop scientific recommendations for optimal cutting practices

for these plants. This approach to the research will support the improvement of privet (*Ligustrum*) cultivation methods and contribute to the development of more effective strategies for producing high-quality, uniform planting material that can be used in urban landscaping.

Materials and Methods

Studies on vegetative propagation of species and cultivars of the genus *Ligustrum* were conducted during the period 2022-2024. During the study,

ethical standards outlined in the following were adhered to Convention on Biological Diversity (1992) and Convention on the Trade in Endangered Species of Wild Fauna and Flora (1973).

The research used species of the genus *Ligustrum* L. and their cultivars, in particular: *Ligustrum vulgare* L., *L. vulgare* 'Atrovirens', *L. vulgare* 'Aurea', *Ligustrum ovalifolium* Hassk., *L. ovalifolium* 'Aureum', *L. ovalifolium* 'Green Diamond', *L. ovalifolium* 'Vicaryi', *Ligustrum ibota* 'Musli', *Ligustrum japonicum* 'Green Century' (Fig. 1).

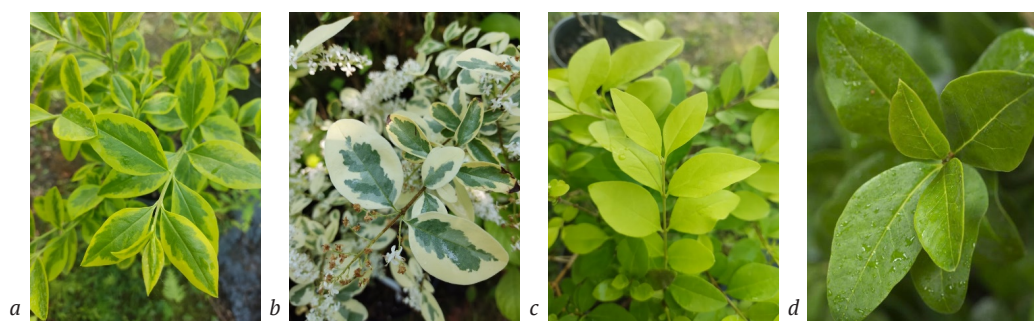


Figure 1. Decorative qualities of leaves of mother plants of certain cultivars of the *Ligustrum* L. **Note:** a – *L. ovalifolium* 'Aureum', b – *Ligustrum ibota* 'Musli', c – *L. ovalifolium* 'Vicaryi', d – *L. ovalifolium* 'Green Diamond'

Source: photos made by the authors

In general, such an assortment of species and cultivars was due to a wide range of shapes and colours of leaves, their most frequent use in landscaping, and the availability of these plants in garden centers and nurseries of Ukraine. All the mentioned plants grow both in open ground and in container culture, in particular *Ligustrum ibota* 'Musli', *Ligustrum japonicum* 'Green Century', in the nursery of the Educational-scientific-production laboratory of tree nursery, reproduction of forests and land reclamation of the department of reproduction of forests and forest land reclamation of the National University of Life and Environmental Sciences of Ukraine.

Mother plants, from which cuttings were taken, were aged from 3 to 5 years. There were no signs of damage by pests or diseases. As for

growing conditions, these plants grew on soils of medium fertility and moisture in partial shade. Propagation of experimental plants was carried out by two methods, lignified – winter, and green – summer cuttings (Maurer, 2019), in greenhouse conditions.

The method of propagation by lignified and green cuttings was carried out according to the methods used by the botanical garden of the National Academy of Sciences of Ukraine (Kolesnichenko *et al.*, 2008), however, the main methods of propagation were adapted in the author's modification, taking into account the characteristics of the species and cultivars of the studied plants. In the process of reproduction by lignified cuttings from mother plants during the rest period, at the end of February,

the beginning of March, shoots were pre-cut, from which cuttings of 8-10 cm size were subsequently formed, approximately 3-4 buds, such cuttings were 5-8 mm in diameter, the upper section is straight, the lower one at an angle of 45°. In the process of planting, the cuttings were deepened by 50-60% of the total length.

When propagating with green – summer cuttings, cuttings from the current year's shoots were used, which actually finished or are finishing their growth and did not have time to become woody, in particular, the period was chosen from the end of July to the beginning of August. The length of the cuttings was on average 5-8 cm, with one or two internodes (however, in the case of *Ligustrum ibota* 'Musli', the number of internodes was 4-5, due to the peculiarity of the shoot structure). Accordingly, the upper cut was made 1 cm above the leaf petiole, and the lower one 1-3 cm below the petiole. Also, in order to prevent excessive evaporation of moisture, the leaf plates were cut in half. The temperature regime in this method was 25-30 °C and air humidity – 85-95%.

For rooting, clean river sand (II in the table) and a mixture of river sand with neutral peat in a ratio of 1:2 (I in the table) was used as a substrate. As an auxiliary factor for improving rooting indicators, powdered preparations (powder) that stimulate the formation of roots were also used. Accordingly, the content of the active substance in these preparations is indicated by the manufacturers as follows, Rizopon AA Proszek 1% – 5-(3-indolylbutyric acid) 9.9 g/kg, Heteroauxin Super – indolyl-3-acetic acid potassium salt 50 g/kg, Grandis-Indolyl-3-butyric acid 6 g/kg.

The peculiarity of the use of these drugs was to apply the powder to the lower section of the cuttings, for both methods, the same length of 1-1.5 cm. Measurement results were presented as mean \pm standard error ($\bar{x} \pm SE$). The significance of the difference ($p < 0.05$) between the obtained data was determined by the method of variance analysis (one-way ANOVA) using Tukey's a posteriori test in the XLSTAT program.

Results and Discussion

When carrying out a comprehensive analysis of the influence of propagation methods, type of substrate and the use of stimulators on the rooting of green and lignified cuttings of various species and cultivars of privet (*Ligustrum*), special attention was paid to the comparisons between the different stimulators of root formation and their rooting conditions.

The obtained results indicate a significant variability of rooting percentages depending on the applied methods and rooting conditions. It was found that some types of privet responded better to certain stimulants and conditions, while others were less sensitive to the changed factors and showed a mediocre rooting result.

When propagating by lignified cuttings, the rooting of all studied cultivars and species is partially different (Table 1). Thus, under control conditions, that is, without the use of drugs, the highest rooting rate of 90.2-92.0% is in *Ligustrum vulgare* L. and its cultivars 'Atrovirens', 'Aurea' (Fig. 2), in the first (peat+sand) substrate, when using the second (sand) substrate, rooting is somewhat less, and varies in all plants differently.

Table 1. Indicators of the percentage of rooting of lignified cuttings, with the use of root formation stimulators

No.	The name of the plant	Control, %		Type of rooters					
				Rizopon, %		Heteroauxin super, %		Grandis, %	
		Substrate	I	II	I	II	I	II	I
1	<i>Ligustrum vulgare</i> L.	90.2 ^{±1.48}	89.6 ^{±1.14}	95.4 ^{±0.55}	91.4 ^{±1.34}	92.4 ^{±1.52}	89.8 ^{±0.45}	93.6 ^{±0.55}	90.4 ^{±0.55}
2	<i>L. vulgare</i> 'Atrovirens'	93.6 ^{±0.89}	88.8 ^{±2.17}	96.2 ^{±1.64}	93.8 ^{±0.84}	92.2 ^{±1.64}	91.0 ^{±1.00}	94.4 ^{±2.07}	92.6 ^{±1.67}
3	<i>L. vulgare</i> 'Aurea'	91.8 ^{±2.28}	85.0 ^{±1.58}	94.6 ^{±1.14}	91.2 ^{±1.10}	91.6 ^{±0.55}	86.4 ^{±0.89}	91.0 ^{±1.22}	89.6 ^{±1.52}
4	<i>L. ovalifolium</i> Hassk.	89.4 ^{±1.95}	85.8 ^{±1.64}	92.2 ^{±1.30}	91.0 ^{±1.00}	92.0 ^{±1.22}	90.0 ^{±0.71}	89.8 ^{±1.48}	88.2 ^{±1.30}
5	<i>L. ovalifolium</i> 'Aureum'	65.6 ^{±0.89}	59.6 ^{±1.52}	84.8 ^{±0.45}	78.8 ^{±1.30}	85.0 ^{±0.71}	77.2 ^{±0.84}	82.8 ^{±0.45}	75.6 ^{±1.14}
6	<i>L. ovalifolium</i> 'Green Diamond'	82.5 ^{±1.56}	73.8 ^{±1.30}	84.4 ^{±0.55}	77.8 ^{±1.30}	80.0 ^{±1.58}	75.0 ^{±1.00}	80.2 ^{±1.79}	77.2 ^{±0.84}
7	<i>L. ovalifolium</i> 'Vicaryi'	92.0 ^{±1.58}	82.4 ^{±1.34}	91.3 ^{±1.16}	88.2 ^{±1.64}	90.4 ^{±0.89}	84.4 ^{±1.14}	91.0 ^{±0.71}	84.8 ^{±1.30}
8	<i>Ligustrum ibota</i> 'Musli'	12.4 ^{±2.06}	9.8 ^{±0.84}	13.1 ^{±1.14}	14.0 ^{±1.4}	14.4 ^{±2.07}	12.6 ^{±2.30}	13.2 ^{±2.05}	12.0 ^{±1.58}
9	<i>Ligustrum japonicum</i> 'Green Century'	67.1 ^{±0.51}	55.0 ^{±2.45}	66.2 ^{±0.84}	62.8 ^{±0.45}	47.0 ^{±2.35}	54.2 ^{±1.64}	51.4 ^{±1.67}	56.2 ^{±1.30}

Note: the significance of the difference $p < 0.05$

Source: developed by the authors

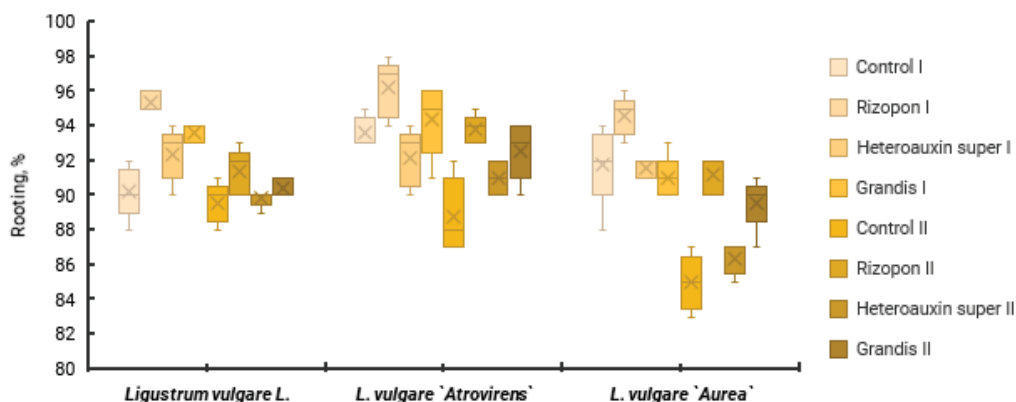


Figure 2. Results of rooting of lignified cuttings of *Ligustrum vulgare* L. and cultivars 'Atrovirens', 'Aurea'

Source: developed by the authors

In particular, *Ligustrum vulgare* L. cultivars, as well as two plants of *L. ovalifolium* Hassk, showed relatively good results and *L. ovalifolium* 'Vicaryi'. In turn, *L. ovalifolium* 'Aureum' and

Ligustrum japonicum 'Green Century' showed mediocre results of rooting, and amounted to no more than 65-67%. *Ligustrum ibota* 'Musli' had the worst rooting rates in the control

conditions, namely 9.8%, although the use of the first substrate had a more positive effect on its rooting, and is 12.4%.

According to the results of the use of root formation preparations, it is possible to see positive dynamics in the rooting of almost all experimental privet plants. The most optimal

variant of the stimulator was Rizopon, %, in contrast to the control, the percentage of rooting increased on average by almost 5% for all plants. *Ligustrum vulgare* L. has the highest indicators – 95.4%, *L. vulgare* ‘Atrovirens’ – 96.2% (Fig. 3) in the first substrate, and 93.8% in the second.

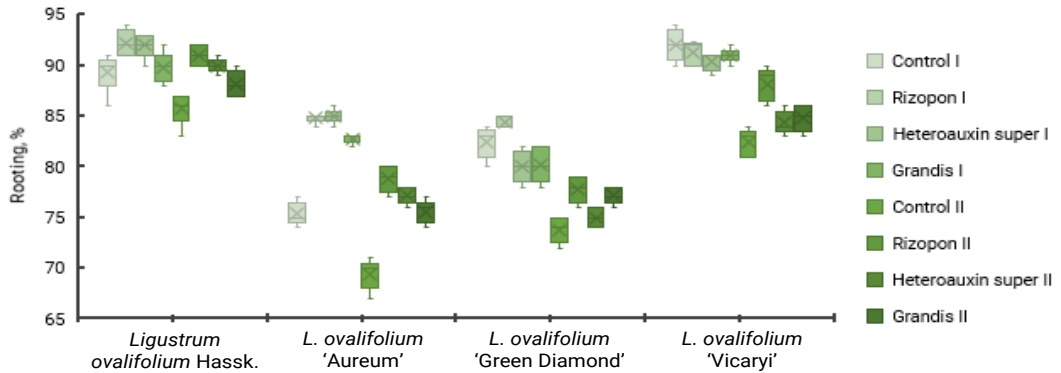


Figure 3. Results of rooting of lignified cuttings of *Ligustrum ovalifolium* Hassk. and its cultivars ‘Aureum’, ‘Aurea’, ‘Green Diamond’, ‘Vicaryi’

Source: developed by the authors

In the case of *L. ovalifolium* ‘Aureum’, ‘Vicaryi’ (Fig. 3), the use of rooting drugs generally has a positive effect on the formation of roots, and an increase in results up to almost 20% is observed in fact for all drugs, which cannot be said for *Ligustrum japonicum* ‘Green Century’ (Fig. 4) when using stimulants, there was no desired increase in rooting rates. *Ligustrum ibota* ‘Musli’ (Fig. 4) reacted positively to the use of drugs, but still the percentage of rooting is extremely small, and is 14.4%, when using Heteroauxin super. Comparing the rooting results of all three drugs, the most optimal for use was Rizopon, and to a lesser extent Grandis, in relation to Heteroauxin super, a positive rooting dynamics is observed, but it differs from the control conditions by a not very large percentage. As in the control conditions, the first substrate (peat+sand) is the best for rooting almost all

plants, but the rooting of *Ligustrum japonicum* ‘Green Century’ in the second substrate (sand) turned out to be an order of magnitude higher under the condition of using rooting preparations, on average this percentage was 4%-7%, which is not observed in control conditions.

The condition of the root system for all studied species and cultivars of privet is good, although the intensity of branching in individual cultivars was much greater, and even the average number of roots in rooted cuttings differed. Thus, *Ligustrum vulgare* L. (Fig. 5a), *L. vulgare* ‘Atrovirens’ (Fig. 5b) and *L. vulgare* ‘Aurea’ (Fig. 5c) had a more branched root system. The formation of roots was observed along the entire length of the cutting, starting from the soil surface, that is, the roots of these plants were formed not only from the lower section of the cutting, but also from

lentils, which are characteristic of this species and its cultivars. The average number of roots for *Ligustrum vulgare* and cultivars was about 12-15 sproutings. Also, intensive branching of secondary roots was observed in these plants, which was not observed in other plants. Root formation in *L. ovalifolium* Hassk., *L. ovalifolium* 'Aureum' (Fig. 5d), *L. ovalifolium* 'Green Diamond' (Fig. 5e) and *L. ovalifolium* 'Vicaryi' (Fig. 5f) occurred only from the lower section

of the cuttings, since this species and its cultivars do not have such an intensive formation of lentils on the shoots, or according to observations, they are absent at all. In general, root formation in all cultivars, including the species plant, is similar. The average number of roots also ranges from 8 to 11 sproutings. In contrast to *Ligustrum vulgare*, intensive formation of second-order roots was not observed in these plants.

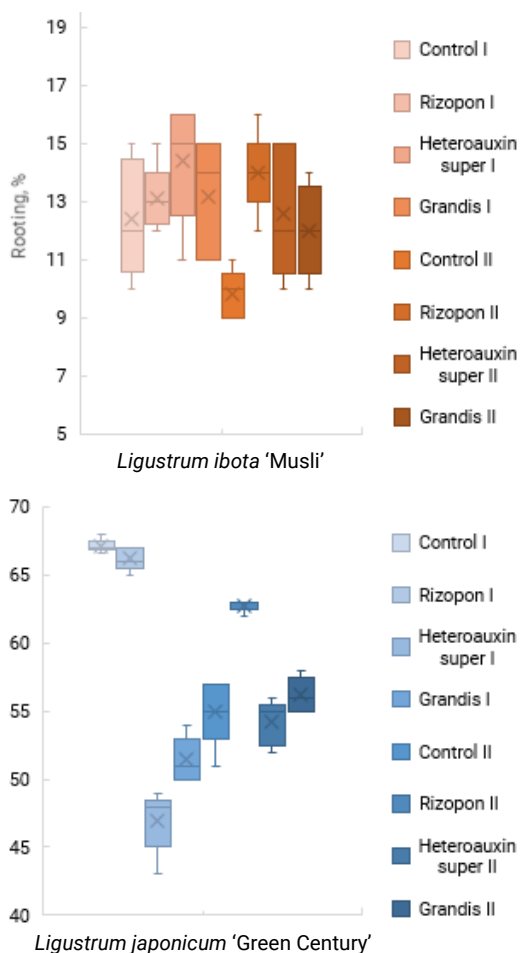


Figure 4. Results of rooting of lignified cuttings of *Ligustrum ibota* 'Musli' and *Ligustrum japonicum* 'Green Century'

Source: developed by the authors

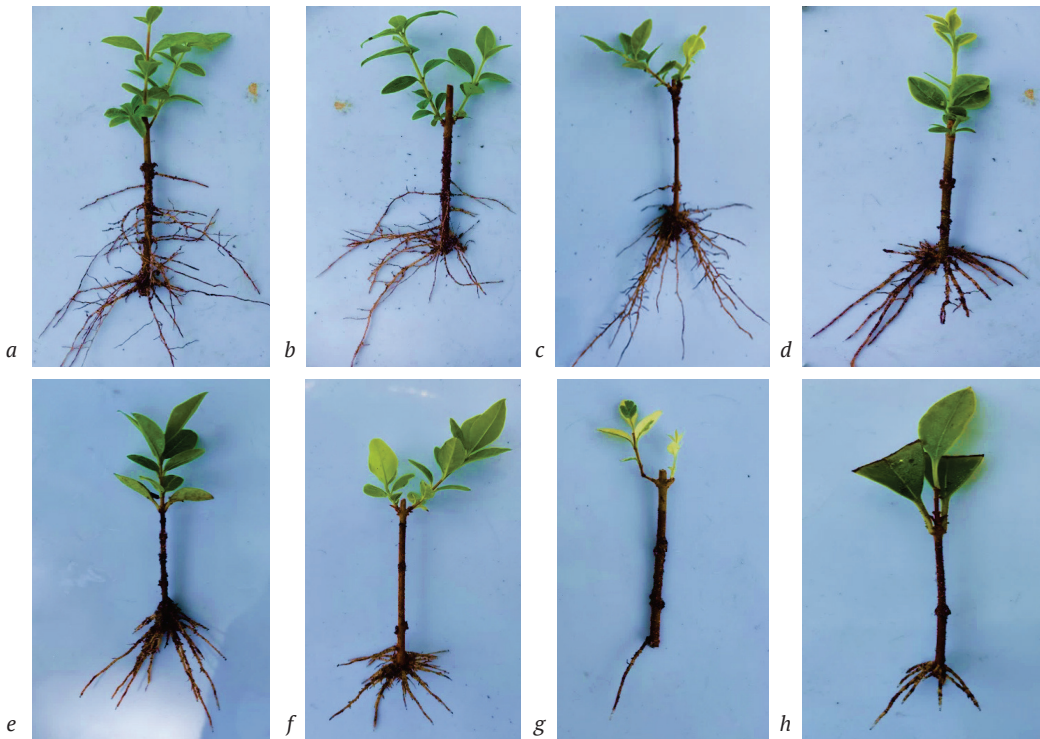


Figure 5. The nature of the development of the root system by lignified cuttings of privet species and cultivars, when using the stimulator Rizopon

Note: a – *Ligustrum vulgare* L, b – *L. vulgare* 'Atrovirens', c – *L. vulgare* 'Aurea', d – *L. ovalifolium* 'Aureum', e – *L. ovalifolium* 'Green Diamond', f – *L. ovalifolium* 'Vicaryi', g – *Ligustrum ibota* 'Musli', h – *Ligustrum japonicum* 'Green Century'

Source: photos made by the authors

The character of the development of the root system in *Ligustrum japonicum* 'Green Century' (Fig. 5h) is not bad, however, unlike *L. vulgare* and *L. ovalifolium*, the intensity of root growth in this plant is somewhat slowed down. The average number of roots was 4-6 sproutings. A characteristic feature of this plant is that the formed roots, although not long, have a comparatively greater thickness, approximately 1.5-2 times greater than those of other cultivars

and species. *Ligustrum ibota* 'Musli' (Fig. 5g) has the lowest rooting rates among experimental plants (Table 1). In general, the development of roots in this plant is also not satisfactory, since the number of roots on all rooted cuttings was mostly 1-2 sproutings.

In contrast to propagation by lignified cuttings, rooting results from green cuttings are somewhat lower, and also vary under different conditions and for different plants (Table 2).

Table 2. Indicators of the percentage of rooting of green cuttings, with the use of stimulators of root formation

No	The name of the plant	Control, %		Type of Rooters					
				Rizopon, %		Heteroauxin super, %		Grandis, %	
	Substrate	I	II	I	II	I	II	I	II
1	<i>Ligustrum vulgare</i> L.	86.8 ^{±1.10}	85.0 ^{±1.22}	91.2 ^{±0.84}	89.8 ^{±0.45}	90.2 ^{±0.45}	88.0 ^{±1.22}	91.0 ^{±2.24}	87.8 ^{±1.10}
2	<i>L. vulgare</i> 'Atrovirens'	88.8 ^{±0.44}	82.2 ^{±1.30}	91.0 ^{±0.71}	87.2 ^{±0.84}	87.6 ^{±0.55}	83.6 ^{±1.82}	89.4 ^{±1.52}	85.4 ^{±1.52}
3	<i>L. vulgare</i> 'Aurea'	83.4 ^{±0.89}	83.2 ^{±1.30}	89.2 ^{±1.92}	87.2 ^{±1.64}	87.6 ^{±2.41}	85.4 ^{±0.55}	88.4 ^{±2.41}	85.4 ^{±2.41}
4	<i>L. ovalifolium</i> Hassk.	84.2 ^{±2.39}	77.6 ^{±2.07}	88.8 ^{±0.45}	83.8 ^{±1.95}	83.6 ^{±1.67}	78.6 ^{±1.95}	86.4 ^{±2.70}	81.4 ^{±2.30}
5	<i>L. ovalifolium</i> 'Aureum'	81.0 ^{±1.04}	75.6 ^{±1.14}	94.8 ^{±1.05}	89.0 ^{±0.00}	91.4 ^{±0.55}	83.8 ^{±1.92}	89.6 ^{±1.82}	84.8 ^{±0.84}
6	<i>L. ovalifolium</i> 'Green Diamond'	74.6 ^{±0.89}	70.2 ^{±1.48}	86.6 ^{±1.14}	81.2 ^{±0.84}	83.0 ^{±1.41}	76.0 ^{±1.22}	84.2 ^{±5.05}	81.8 ^{±1.30}
7	<i>L. ovalifolium</i> 'Vicaryi'	82.5 ^{±1.39}	75.4 ^{±0.89}	83.6 ^{±0.89}	76.4 ^{±2.07}	81.4 ^{±3.78}	75.8 ^{±1.50}	83.2 ^{±2.05}	75.4 ^{±1.67}
8	<i>Ligustrum ibota</i> 'Musli'	34.9 ^{±2.43}	35.8 ^{±2.39}	66.5 ^{±1.66}	68.4 ^{±0.55}	66.2 ^{±4.60}	68.4 ^{±2.41}	66.0 ^{±2.83}	64.2 ^{±2.77}
9	<i>Ligustrum japonicum</i> 'Green Century'	21.0 ^{±2.94}	17.0 ^{±2.24}	42.8 ^{±2.86}	38.0 ^{±2.55}	41.8 ^{±2.77}	33.0 ^{±2.24}	44.0 ^{±2.65}	35.2 ^{±2.39}

Note: the significance of the difference $p < 0.05$

Source: developed by the authors

Control samples *Ligustrum vulgare* L. (Fig. 6), *L. ovalifolium* Hassk. (Fig. 7) and their cultivars mostly have similar rooting results, and the difference in the number of rooted cuttings both in the first and in the second substrates is not very different. In general, when using a substrate made of peat and sand, the quantitative indicator of rooting is 2-5% higher, in contrast to pure sand, precisely for these plants. However, considering two other species, in particular *Ligustrum ibota* 'Musli' and *Ligustrum japonicum* 'Green Century' (Fig. 8), it was

shown completely different dynamic. Thus, the percentage of rooting by green cuttings of *Ligustrum ibota* 'Musli' is actually three times higher than propagation by lignified cuttings, although in general this result is not satisfactory and is only 34-35%. *Ligustrum japonicum* 'Green Century', in contrast to the method of propagation by lignified cuttings, showed a much worse result. The percentage of rooting in the control sample in two substrates was 17-21%, which is 2.5 times less compared to lignified cuttings.

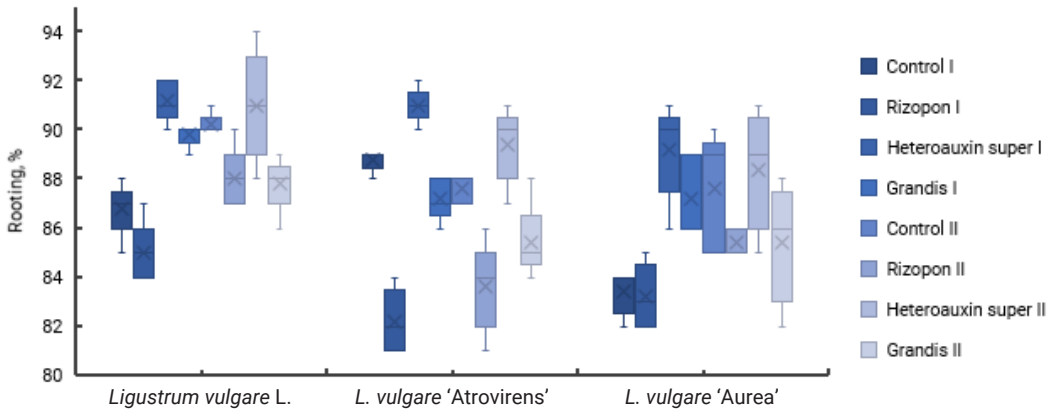


Figure 6. Rooting results of green cuttings of *Ligustrum vulgare* L. and cultivars 'Atrovirens', 'Aurea'

Source: developed by the authors

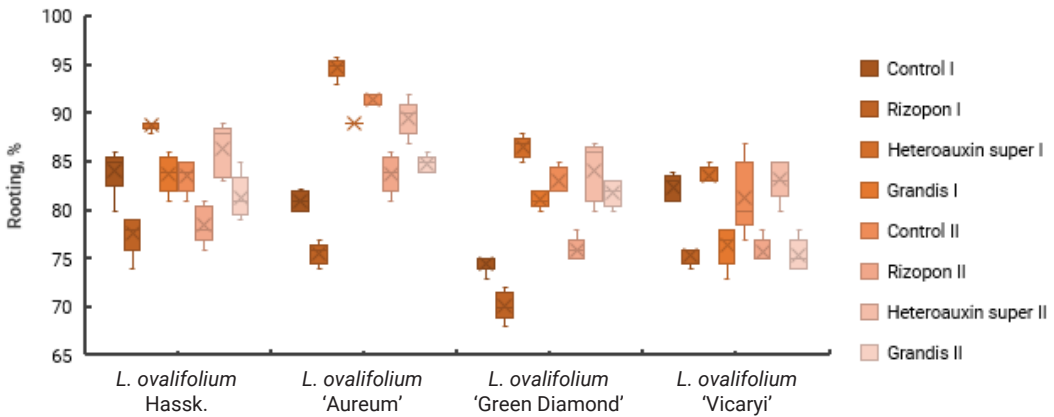


Figure 7. Rooting results of green cuttings of *Ligustrum ovalifolium* Hassk. and its cultivars 'Aureum', 'Aurea', 'Green Diamond', 'Vicaryi'

Source: developed by the authors

Rooting indicators with the use of rooting stimulants also remain relatively stable. According to the results of Table 2, it is possible to follow the same dynamics as in the case of propagation by lignified cuttings, that is, the highest percentage of rooting in all plants is observed when using Rizopon rooting agent, the quantitative indicators of rooting with its use are increased

by 3-5%. The highest rates of rooting when using this drug can be seen in the following plants: *Ligustrum vulgare* L. – 91.2%, *L. vulgare* 'Atrovirens' – 91.0% (Fig. 6) and *L. ovalifolium* 'Aureum' (Fig. 7) with the highest rate – 94.8%. In particular, these results were obtained when using the first substrate (peat + sand, 1:1), but in pure river sand the percentages are slightly lower.

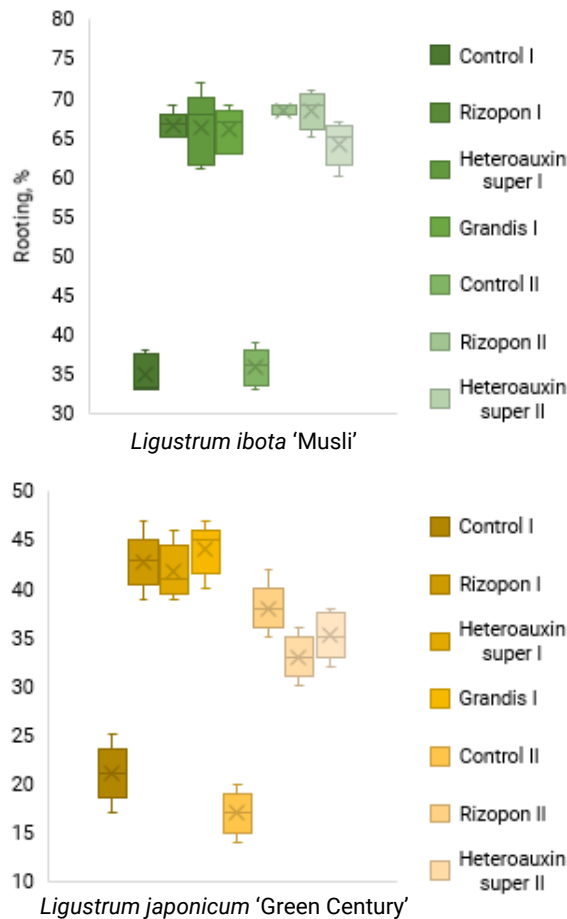


Figure 8. Rooting results of green cuttings of *Ligustrum ibota* 'Musli' and *Ligustrum japonicum* 'Green Century'

Source: developed by the authors

In turn, the percentage of rooting that exceeds 90 can also be observed with the use of other drugs, in particular with the use of "Heteroauxin super", good results are obtained in *Ligustrum vulgare* L. – 90.2% (Fig. 6), and *L. ovalifolium* "Aureum" – 91.4% (Fig. 7) while when using the Grandis stimulator, a high rate of rooting is noticeable only in *Ligustrum vulgare* L. – 91.0%, the tendency of better rooting in the first substrate usually remains.

L. ovalifolium Hassk. (Fig. 7) and its cultivars generally responded positively to the use of root-forming preparations. Thus, the rate of rooting varies between 81-88%. Using a mixture of peat and sand (1:2) as a substrate shows positive dynamics for these plants. When using *L. ovalifolium* 'Vicaryi' as pure river sand (Fig. 7), the quantitative index of rooting is significantly lower in contrast to the main substrate, and ranges from 75.4% to 76.4%,

while the use of the first substrate (peat + sand) showed 81.4%-83.6%.

It is also necessary to note the positive dynamics of rooting with green cuttings for *Ligustrum ibota* 'Musli'. Compared to the results of rooting with lignified cuttings in this case, the percentage of rooting is actually 2-3 times higher. In particular, in the control conditions, it was only 34.9-35.8% (Fig. 8), and already with the application of rooting preparations, the rooting indicators actually doubled: Rizopon – 68.4%; Heteroauxin super – 68.4%; Grandis – 64.2%. It is also worth noting that *Ligustrum ibota* 'Musli' has somewhat higher percentages of rooting in clean river sand.

Regarding the rooting of *Ligustrum japonicum* 'Green Century' (Fig. 8), it can be noted that when propagating with green cuttings, the

number of rooted cuttings is slightly less than the method of propagating with lignified cuttings. Accordingly, in the control conditions in the first substrate 21.0%, and with the use of drugs this indicator ranges from 41.8 to 44.0%.

The development of the root system when propagated by green cuttings, as in the case of lignified cuttings, differs depending on the species. The principle of root formation in *Ligustrum vulgare* L. (Fig. 9a) and its cultivars 'Atrovirens' (Fig. 9b) and 'Aurea' (Fig. 9c) is similar to lignified cuttings, i.e. root growth takes place along the entire length of the cutting, including the lower cuts and nodes. The average number of well-developed roots was 6-9 sproutings. Also, to a greater extent, the formation of roots of the second order is characteristic for a species plant, while their formation is less intense in cultivars.

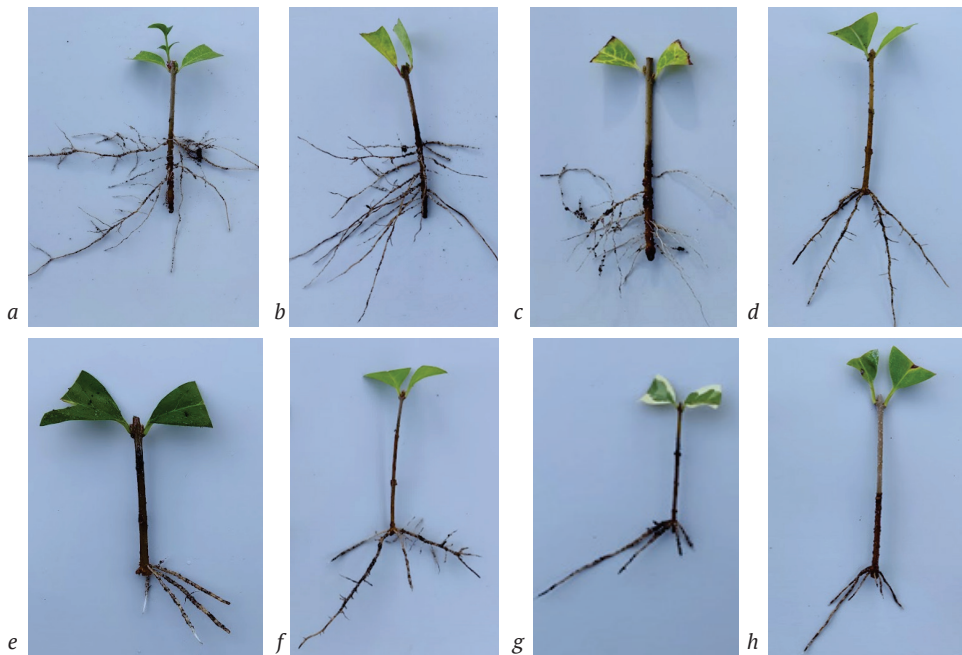


Figure 9. The character of the development of the root system, when propagating by green cuttings, species and cultivars of privet, after using the stimulator Rizopon

Note: a – *Ligustrum vulgare* L., b – *L. vulgare* 'Atrovirens', c – *L. vulgare* 'Aurea', d – *L. ovalifolium* 'Aureum', e – *L. ovalifolium* 'Green Diamond', f – *L. ovalifolium* 'Vicaryi', g – *Ligustrum ibota* 'Musli', h – *Ligustrum japonicum* 'Green Century'

Source: photos made by the authors

Formation and development of roots in *Ligustrum ovalifolium* Hassk. and cultivars 'Aureum' (Fig. 9d), 'Green Diamond' (Fig. 9e) and 'Vicaryi' (Fig. 9f) is markedly different from *Ligustrum vulgare*. In particular, root growth takes place only from the lower section of the cutting. The average number of roots for this species and cultivars is uniform for all and varies between 3-4 sproutings. It is also possible to note the formation of roots of the second order, while cuttings of *L. ovalifolium* 'Green Diamond' (Fig. 9e) did not form such roots. It is worth noting that, in general, the process of rooting and root development of *Ligustrum ibota* 'Musli' (Fig. 9g) and *Ligustrum japonicum* 'Green Century' (Fig. 9h), is much better when propagated by green cuttings. The average number of roots was 4-5 pieces, and the growth of second-order roots also began to some extent in *Ligustrum ibota* 'Musli', however, in *Ligustrum japonicum* 'Green Century' the development of such roots was not observed. The formation of roots occurred mainly from the lower part of the cuttings.

The production of high-quality planting material is always relevant, as it ultimately determines the viability and longevity of green plantings, their ornamental appeal, and aesthetic value. For this reason, the propagation of plants is a subject of study for researchers across various disciplines.

In his work, V.M. Novosad (2014) described the reproduction of *Ligustrum vulgare* L. by vegetative and generative methods. Among the main aspects of the technique that was used, the following can be noted: propagation was carried out by green cuttings in the summer, their length was 10-15 cm. In turn, propagation was carried out in open ground. Rooting rates ranged from 70 to 100%. On opinion, propagation by this method in the open ground under the condition of a constant increase in temperature every year is quite problematic, as there is a need for constant control of the rooting conditions. The author also describes the

process of propagation of *Ligustrum vulgare* L. and *Ligustrum ovalifolium* 'Aureum' using the same method, although the cuttings were planted in greenhouses during intensive growth, in particular before the flowers bloom. Thus, the results of this experiment were quite low, and in general amounted to 10-20%. On opinion, such a result was caused by failure to comply with the terms of harvesting cuttings, since during this period the shoots are just beginning to grow and do not have the potential to root. V.M. Novosad (2014) also explored the process of propagation of *Ligustrum vulgare* L. by lignified cuttings where the amount of rooted material was more than 80%. In the conclusions, the author recommended green cuttings, since the number of rooted cuttings was the highest, although the method of propagation by lignified cuttings also showed a high result. According to observations, in particular, in controlled greenhouse conditions, it will be better to use lignified cuttings.

Ligustrum vulgare L. was also propagated by A.V. Melnyk & V.S. Tokman (2023). In their research, they examined the process of propagating privet by lignified cuttings, where planting was carried out in greenhouse conditions. The main emphasis in this work was on the thickness of the cutting material. In particular, the author noted that as the thickness of the cuttings increases, there was an improvement in the biometric indicators of such material. In their work, they took shoots with a thickness of 5 mm to 8 mm. After rooting, parameters of cuttings were measured. The most productive was the material with the largest thickness – 8 mm, and the increase in above-ground and mass and mass of the root system in comparison with the thinnest cuttings – 5 mm was 215%. It was taking into account this approach to the propagation of *Ligustrum vulgare* L., however, taking into account the morphometric and biological features of the studied species and cultivars, certain corrections were made.

Propagation of *Ligustrum vulgare* was also carried out by J. Hansen & K. Kristiansen (2000). In their research, they described the rooting process of cuttings, where they paid special attention to the influence of the date of planting and the location of the experiment on the percentage of rooting. The authors noted that the percentage of rooting was significantly higher in the second year of the experiment (75%) compared to the first (60%). In addition, rooting of cuttings was found to be about 80% by September 10, after which this rate dropped sharply to 20% for planting in October. However, bud growth and plant survival were largely independent of the date of planting or location of the experiment. It was taking into account such regularities in the process of conducting the research, but made certain corrections taking into account the biological features of *Ligustrum* species and cultivars.

In their study, M.J. Monder & A. Pacholczak (2023) demonstrated the effects of biostimulants and rooting agents such as auxins on plant development processes. It is important to note that among the preparations used were powders containing 0.4% indolylbutyric acid (IBA) and 0.2% naphthylacetic acid (NAA), as well as plant extracts, in particular preparations based on seaweed and humic substances. These rooting stimulants affected the content of polyphenolic acids in plants, which may indicate their participation in rhizogenesis processes. Although changes in polyphenol content were not clearly correlated with rooting percentage or cutting quality, their effect on rooting activation was significant.

N. Aguirre-Acosta *et al.* (2023) studied the genetic diversity of *Ligustrum lucidum* (glossy privet) in fragmented habitats in Argentina. They found lower genetic diversity in fragmented populations, but age-related effects reduced fragmentation impact. Younger trees had higher diversity, suggesting multiple introduction

events. The study highlighted that bird-mediated seed dispersal maintains landscape connectivity and enhances genetic diversity.

Several studies have examined the ecological and horticultural aspects of *Ligustrum*, contributing to the improvement of propagation techniques for urban applications. Y. Wang *et al.* (2024) explored the phylogenetic diversity and interspecies competition within *Ligustrum* species, focusing on the adaptive radiated varieties. The study highlighted the impact of evolutionary processes on species diversity, which was important for selecting *Ligustrum* species suited for urban greening. The findings suggested that understanding phylogenetic relationships could guide the selection of robust cultivars with better adaptability to urban conditions.

Scientists J.J. Rycyna *et al.* (2024) evaluated three *Ligustrum* cultivars in Florida, assessing both their landscape performance and fruit characteristics. The study provided valuable insights into the ornamental and functional benefits of different *Ligustrum* cultivars for urban green spaces, particularly in terms of aesthetic appeal and ease of maintenance. The findings indicated that *Ligustrum* cultivars varied in their growth habits and resilience, which was vital when selecting the best material for urban greening projects.

Collectively, these studies contributed to a deeper understanding of the ecological, horticultural, and agronomic features of *Ligustrum*, providing a basis for improving propagation technologies. Efficient propagation methods, such as cuttings and tissue culture, were essential for producing uniform and healthy planting material, ensuring successful urban greening initiatives. In this study, rooting stimulants were also used for propagation of *Ligustrum* species and cultivars, confirming their effectiveness in increasing rooting percentage in different plant species.

Conclusions

As a result of the conducted research aimed at improving the technology for growing privet (*Ligustrum*) planting material and its cultivars for urban landscaping, it can be noted that the use of rooting stimulators is quite effective. The most positive impact on the rooting of both green and woody cuttings was observed with the Rizopon preparation, which, on average, increased the rooting percentage by 5-10% compared to the control. The highest rooting rates were observed with *Ligustrum vulgare* L. and its cultivars 'Atrovirens' and 'Aurea', reaching up to 96% rooting when using this preparation. The factor of using the substrate is also quite important, in particular, the substrate based on peat and river sand (2:1) is the most optimal for most of the studied species and cultivars, providing better rooting compared to clean river sand. As for *Ligustrum ibota* 'Musli', the optimal substrate for rooting was pure river sand.

The method of propagation by lignified cuttings is the most optimal for such species as *Ligustrum vulgare* L., *Ligustrum ovalifolium* Hassk. and most of their cultivars. The percentage of rooting compared to green cuttings is 4-6 units higher. In addition, the rooting rates of *Ligustrum japonicum* 'Green Century' are also much higher when used for propagating lignified cuttings. While *Ligustrum ibota* 'Musli' showed better results when propagated by green cuttings, here quantitative indicators of rooting were 25-40% higher. Intensive branching of the root system was also

observed in *L. vulgare* cuttings, especially when stimulants were used. In other species (for example, *L. ovalifolium* 'Aureum'), root formation was concentrated mainly in the lower part of the cuttings.

Thus, during the further cultivation of rooted cuttings, must be obtained high-quality planting material of privet species and cultivars, which can later be used in the creation of various landscaping elements. For example, the species *Ligustrum vulgare* L. and *Ligustrum ovalifolium* Hassk., due to their strong branching of the root system, will be most optimally used for creating live fences near roads. Their cultivars are more suitably used in more protected spaces, in flowerbeds, or at a certain distance from roads, when creating topiary figures or combined colour groups.

Further studies should focus on examining the long-term effects of rooting stimulators on the growth and development of plants after transplanting, as well as optimizing substrate composition to improve rootability. Research could also be aimed at improving plant care technologies after rooting to ensure their stable development and enhance the quality of planting material, which in turn will assist in the use of these plants for city landscaping.

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None.

Conflict of Interest

None.

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Вдосконалення технології вирощування садивного матеріалу рослин роду *Ligustrum L.* для озеленення урбанізованих територій

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Анотація. Актуальність дослідження зумовлена потребою у покращенні якості посадкового матеріалу та розширенні асортименту декоративних рослин для озеленення урбанізованих територій. Метою дослідження було вдосконалення технології розмноження бирючини з урахуванням біологічних особливостей та факторів, що впливають на процес укорінення, таких як використання стимуляторів коренеутворення та вибір субстратів. У результаті порівняння укорінення зелених та здерев'янілих живців встановлено різну ефективність залежно від використаних субстратів і стимуляторів коренеутворення, зокрема препаратів Rizoron, «Гетероауксин супер» та Grandis. Експерименти показали, що найбільш ефективним стимулятором коренеутворення був препарат Rizoron, який підвищував відсоток укорінення живців на 5-10 %, порівняно з контролем. Найвищі показники

укорінення спостерігалися у *Ligustrum vulgare* L. та її культиварів 'Atrovirens' і 'Aurea', досягаючи 96 %. Субстрат на основі торфу та річкового піску (2:1) був найоптимальнішим для більшості видів, тоді як для *Ligustrum ibota* 'Musli' ефективнішим виявилось застосування чистого річкового піску. Результати розмноження здерев'янілими живцями показали на порядок вищий відсоток укорінення для більшості досліджуваних рослин, зокрема, *Ligustrum vulgare* L., та її культиварів, відсоток укорінення коливався в межах 86-96 %, тоді як укорінення зеленими живцями – в межах 85-90 %. У випадку з *L. ovalifolium* Hassk. Дані показники дещо менші, проте були задовільними: здерев'янілі живці 75-92 %, зелені живці 74-90 %. *Ligustrum ibota* 'Musli' та *Ligustrum japonicum* 'Green Century' мали посередні результати укорінення як здерев'янілими так і зеленими живцями, *Ligustrum ibota* 'Musli' при розмноженні здерев'янілими живцями мала результат в межах 12-14 %, і здерев'янілими 66-68%. *Ligustrum japonicum* 'Green Century' має більший відсоток укорінення при розмноженні здерев'янілими живцями 47-62 %. Результати дослідження можна використати для підвищення ефективності розмноження бирючини та вдосконалення технології вирощування якісного посадкового матеріалу стійкого до умов урбанізованого середовища. Ці дослідження слугують інформаційною науковою основою удосконалення систем декоративного розсадництва

Ключові слова: декоративне розсадництво; вегетативне розмноження; зелені насадження; субстрат; укорінюваність; урбосередовище; морфометричні показники

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