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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 m^3 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 *et al.* (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 *et al.* (2018), R. Jandl *et al.* (2019), V. Lavnyy *et al.* (2022), A. Zawadzka & A. Slupska (2022), J. Miettinen *et al.* (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 (*Chamaenerion angustifolium* (L.) Scop., *Calluna vulgaris* (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).

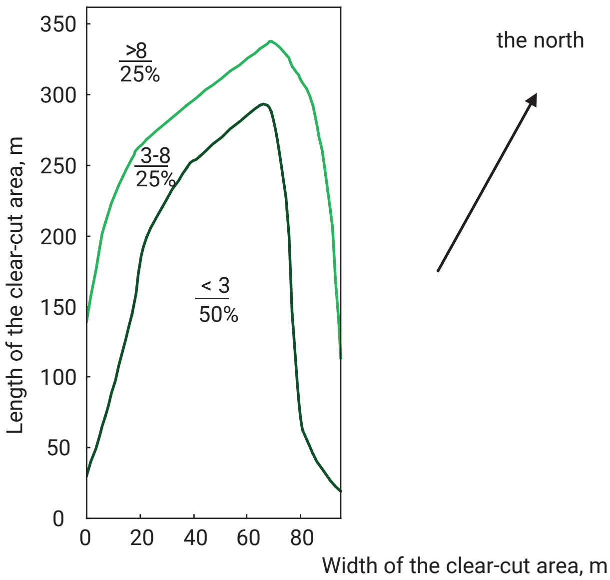

Figure 1. Distribution of natural Scots pine regeneration in fresh subir (B_2) on a one-year-old clear-cut area of Dzvinkivske forestry in Boyarka FRS

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 clearcut 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 (B_3) 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 m^3 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 m^3/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 m^3/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 m^3/ha), and the highest stock levels were found in sections D (436 m^3/ha) and E (420 m^3/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 (B_2), 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 (B2), 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 nonclearcut 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' paleoclimate, 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 Polissia, 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 зрубах 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 зрубах відзначається до 50 м, середнє – на відстані 51-100 м, рідке – більше 100 м від незрубаного лісу. Максимальні запаси (420-436 $м^3$/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