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ANALYSIS OF THE EFFECTIVENESS OF AFFORESTATION TECHNOLOGIES IN THE NORTH-EASTERN FOREST-STEPPE OF UKRAINE

SUMMARY

The study is dedicated to the scientific substantiation of the effectiveness of technologies for creating highly productive and biologically stable forest plantations under the critical conditions of the North-Eastern Forest-Steppe of Ukraine, considering the impact of anthropogenic and climatic challenges that necessitate a shift from monocultures to more sustainable mixed stands. The analysis showed that the conditional survival rate of seedlings is consistently high in all studied forest site types and mixing schemes, exceeding 85%. Furthermore, the dispersion analysis demonstrated that the influence of both the forest site type and the mixing scheme on the average survival rate is statistically insignificant. However, the mensurational inventory of mature stands revealed a significant process of natural thinning, where the proportion of suppressed and dying trees (according to Kraft) reaches over 50% for some species. In view of this, the results obtained underscore that the main focus in afforestation should be shifted from ensuring high initial survival rates to developing strategies for managing mature mixed stands to enhance their long-term stability, resistance, and adaptive capacity to changing climatic conditions.

Keywords: afforestation, mixing schemes, survival, sanitary condition, stability

INTRODUCTION

Creating highly productive forest stands is one of the key tasks of Ukraine's forestry complex, especially amid the anthropogenic impact caused by military actions. The North-Eastern Forest-Steppe of Ukraine, and the Slobozhanshchyna region in general, is one of the areas most affected by the full-scale invasion (Kuzyk and Tovarianskyi, 2023; Kovalzhy *et al.,* 2024; Voitovyk

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et al., 2024a). Therefore, the issue of careful selection and substantiation of afforestation and reforestation technologies is extremely relevant now and will remain so for quite a long time in the future.

On the other hand, climate change is also having a detrimental effect on forest stands. Specifically, a study of Vacek *et al.* (2023) analyzed more than 360 publications between 1993 and 2022 and found that climate change has become quite tangible for European forests, particularly through fires, moisture deficit, or the development of pests, which significantly impacted natural wood increment. This is the other side of the coin that also requires a detailed study of afforestation strategies. The ineffective use of technological approaches leads to low seedling survival rates, reduced biological stability of stands, and, consequently, significant economic losses.

Given the challenges mentioned, the scientific community is paying significant attention to the issues of increasing the effectiveness of forest stand establishment. Specifically, the study of Liu *et al.* (2022) discusses that afforesting drylands creates a dilemma due to conflicting results. Namely, increasing forest cover enhances water consumption through a nonlinear increase in evapotranspiration, a trend that will be deepened by climate change.

The research of Pérez-Silos *et al.* (2021), based on a meta-analysis of 75 publications covering 128 afforestation actions in Spain, found that large-scale afforestation programs of the 20th century improved timber provision and carbon sequestration. At the same time, it was established that afforestation programs did not enhance regulating ecosystem services (ES) and biodiversity conservation compared to natural sites, and were only effective compared to highly degraded areas. Many authors conclude that there is a need to shift towards integrated landscape approaches in afforestation that are not limited solely to productivity criteria (Song *et al.,* 2023; Briske *et al.,* 2024; Enescu *et al.,* 2025).

The research of other scientists focuses on the selection of sustainable tree species (Belmega *et al.*, 2024), the optimization of mixing schemes and planting density (Vasilevskyi *et al.*, 2024), as well as the improvement of soil preparation methods (Varnagirytė-Kabašinskienė *et al.,* 2022). However, most existing scientific works typically focus on individual elements of the technological process (for example, only on the types of planting material or only on methods of mechanized soil cultivation).

Currently, there is a critical deficit of comprehensive studies that would provide a comparative assessment of the entire technological chain of forest stand establishment-from site preparation to tending of young growth-directly under the conditions of the North-Eastern Forest-Steppe of Ukraine. This gap becomes even more significant in light of the need for rapid and effective restoration of forests affected by hostilities (Hryhoriv *et al.*, 2024; Voitovyk *et al.*, 2024b; Datsko *et al.*, 2025) and the adaptation of forest stands to changing climatic conditions.

Unlike most previous studies of afforestation in Ukraine and Eastern European countries, which focused mainly on general silvicultural indicators or regional features of plantation cultivation, this work focuses on a comprehensive analysis of the conditions for growing planting material and its survival in specific forest vegetation conditions. The results obtained allow us to clarify the effectiveness of the applied technologies for creating forest crops and can be used in forestry practice to increase the productivity and stability of artificial plantations. The practical recommendations formulated based on the results of the study are of practical importance for optimizing silvicultural activities in the study region.

In view of the critical deficit of comprehensive regional studies mentioned, this work aims to provide scientific substantiation and a comparative assessment of the effectiveness of the entire technological chain for the establishment of highly productive and biologically stable forest stands under the specific conditions of the North-Eastern Forest-Steppe of Ukraine.

MATERIAL AND METHODS

The research was conducted on the territory of the Sumy Forestry Enterprise, located in the eastern part of the Sumy region, which belongs to the Left-Bank Dnieper Forest-Steppe (according to forest-growing regionalization). The region is situated in the southern wing of the Dnipro-Donetsk Depression on the East European Platform.

The relief is predominantly flat, with elevations ranging from 115 to 230 meters above sea level, marked by the presence of river valleys and ravines (balkas), as well as the floodplains of the Psel River. The soil cover is mainly represented by gray and podzolized soils, as well as dark gray soils and chernozems.

The region's climate is moderately continental, characterized by mild winters and warm summers. The average frost-free period lasts 169 days. The average annual relative air humidity is maintained at about 78%. The prevailing wind direction is south-east, with an average speed ranging from 4.6 m/s (maximum) to 2.4 m/s (minimum). Overall, the natural and climatic conditions of the studied region are favorable for the growth and development of forest vegetation, despite a noticeable trend toward warming.

The objects of the study were artificial forest plantations of various ages, established and grown on the territory of the Sumy Forest District. The research included five inventory sample plots, which were laid out in artificial stands representing the main forest site types of the forestry enterprise (Table 1). To ensure representativeness and assess a wide range of silvicultural approaches and growing conditions, sample plots were selected from the forest inventory and forest plantation records of the forestry unit. Five permanent sample plots were established to assess the condition and productivity of the forest stands. The size of each research plot was determined in strict compliance with current regulatory documents, ensuring a 5% error margin for the forest inventory and the assessment of key forestry indicators (Fig. 1).

Table 1. Detailed Characteristics and Mensurational Indicators of the Research Plots

No. of SP (Sample Plot)	Area, ha	Forest Site Type (FST)	Stand Age, years	Stand Composition	Planting Scheme, m
SP No. 1	2.2	Moist Oak-Pine Undergrowth (V3)	39	8Sc2Qc+B	2.5×0.5
SP No. 2	0.8	Fresh Oak-Pine Undergrowth (B2)	57	10Sc+Bp	2.5×0.7
SP No. 3	1.2	Fresh Pine Forest (B2)	45	9Sc1Bp	2.5×0.5
SP No. 4	3.2	Fresh Conglomerate (C2)	55	7Sc3Qc+Bp	2.5×0.5
SP No. 5	0.6	Fresh Birch Forest (A2)	48	10Sc	2.5×0.6

**Sc – Pine, Qc – Oak, B – Birch, Bp – Silver Birch.*

Figure 1. Research plots of forest plantations

The trial plots established within the studied forestry enterprise represent typical forest vegetation conditions of the North-Eastern Forest-Steppe of Ukraine (fresh subors and sugruds). At the same time, the obtained results primarily characterize the conditions of forestry management of a particular enterprise and can be extrapolated to other forestry objects of the region with similar soil-climatic and technological conditions.

A comprehensive field description was conducted on each sample plot, which included recording the geographic location (quarter, compartment, and area numbers), characterization of forest growth conditions (FGC), and a detailed description of the understory and ground cover (with identification of dominant species such as lingonberry, heather, rowan, and buckthorn). Furthermore, the current sanitary condition of the stands was assessed, and archival data regarding establishment silviculture (year and season of planting, type of planting material, specifically standard seedlings, and the exact planting scheme) were collected.

Tree inventory was conducted stem-by-stem, classified by main species. Tree diameter was measured at a 2 cm interval. Height was measured multiple times for each diameter category with an accuracy of 0.5 m. Stand quality (site index, or bonitet) was assessed using the M.M. Orlov scale, which is based on the ratio of the stand's average age and average height. The sanitary condition of each tree was classified according to the "Sanitary Rules in the Forests of Ukraine". Calculations for stand fullness (the ratio of the actual sum of the cross-sectional areas of the trunks to the normative value) and the stock of stem wood were performed according to generally accepted forest inventory methods.

The results obtained primarily characterize the conditions of forestry management of a particular enterprise and can be extrapolated to other forestry facilities in the region with similar soil, climatic and technological conditions.

To identify the patterns of growth and productivity of the forest stands, as well as to evaluate the influence of various factors (age, FGC, fullness) on the inventory indicators, the software Statistica 10.0 and Microsoft Excel were used.

RESULTS AND DISCUSSION

Figure 1 illustrates the dependence of the average survival rate of forest stands on the five main forest growth condition types (FGC) that are the subject of the study. The overall analysis indicates that seedling survival is relatively high across all studied FGCs, ranging between 89% and 94%. The highest average survival rate was recorded in the B2 Fresh Oak-Pine Forest (Subir), where it is approximately 91.8%, and in the B3 Moist Oak-Pine Forest (Subir) (91.6%). These two condition types also demonstrate the largest range of potential survival, reaching almost 94%. The lowest average survival rate was noted in the A1 Dry Pine Forest (Bir) around 89.8% while this FGC is also characterized by the least variability. The A2 Fresh Pine Forest (Bir) and C2 Fresh Oak-Pine Grove (Sugrud) types demonstrate intermediate values, indicating the consistently high effectiveness of traditional forest regeneration technologies in fresh and moist subors compared to drier conditions.

The results of the analysis of variance (ANOVA), shown in Table 2, indicate that the influence of forest growth condition type (FGC) on the average seedling survival rate is statistically insignificant. Since the p-value (0.74) significantly exceeds the generally accepted significance level of 0.05, there are insufficient grounds to assert that the difference in survival between the studied FGCs is substantial.

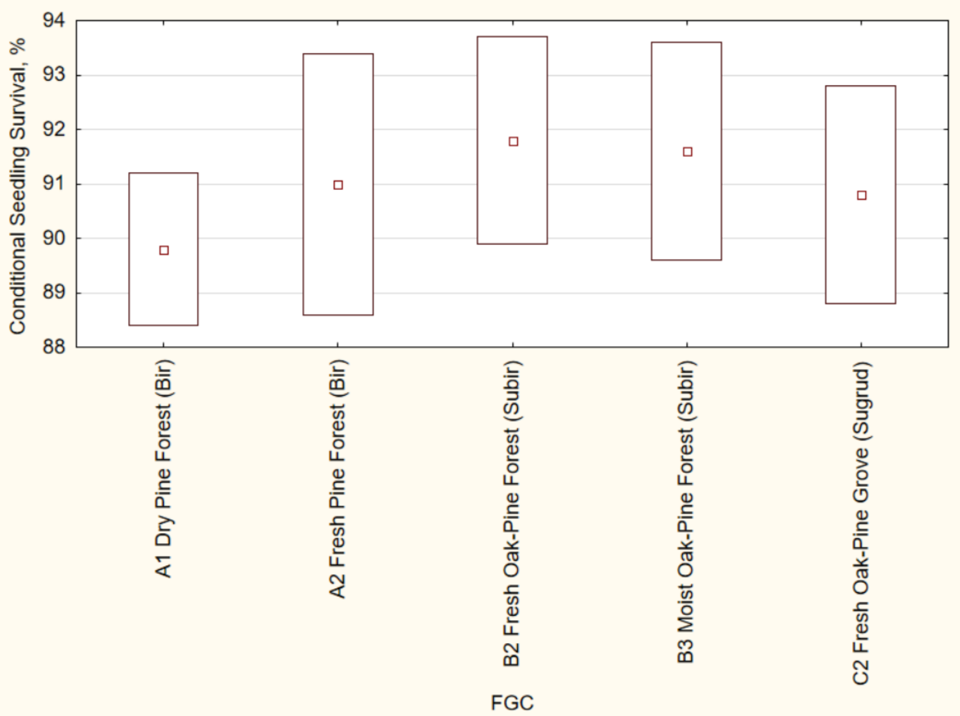

Figure 2. Diagram of the average survival rate of forest stands by forest growth condition types

This implies that the observed differences in average survival rates, as illustrated in Figure 2, can be attributed to randomness rather than the type of growing conditions.

Table 2. Analysis of variance (ANOVA) of the influence of forest growth condition type on conditional seedling survival

Indicator	Sum of Squares – Effect	Degrees of Freedom (df) – Effect	Mean Square – Effect	Sum of Squares – Error	Degrees of Freedom (df) – Error	Mean Square – Error	F-Ratio	p-value
Conditional Seedling Survival, %	7.44	4.0	1.86	38.66	10.0	3.866	0.48	0.74

Figure 3 demonstrates the dependence of the average conditional seedling survival rate on five different forest stand mixing schemes that were the subjects of the study. Overall, all examined schemes ensure high survival rates. The highest average survival value was recorded for the 10Sc+Bp scheme – approximately 91.7% – while the lowest average indicator was observed in the pure pine culture 10Sc – around 89.7%. Furthermore, the 9Sc1Bp scheme demonstrates the greatest variability, reaching a potential maximum of over 93%, and the 7Sc3Qc+Bp and 8Sc2Qc+B schemes have virtually identical average indicators. The consistently high survival in mixed stands may indicate a positive influence of the admixture of deciduous species on the microclimate and soil conditions.

High initial seedling survival (Table 3) characterizes only the establishment stage and does not take into account long-term factors, including competition, climatic stresses, and biotic damage, which manifest themselves at later stages of plantation development and can reduce their stability.

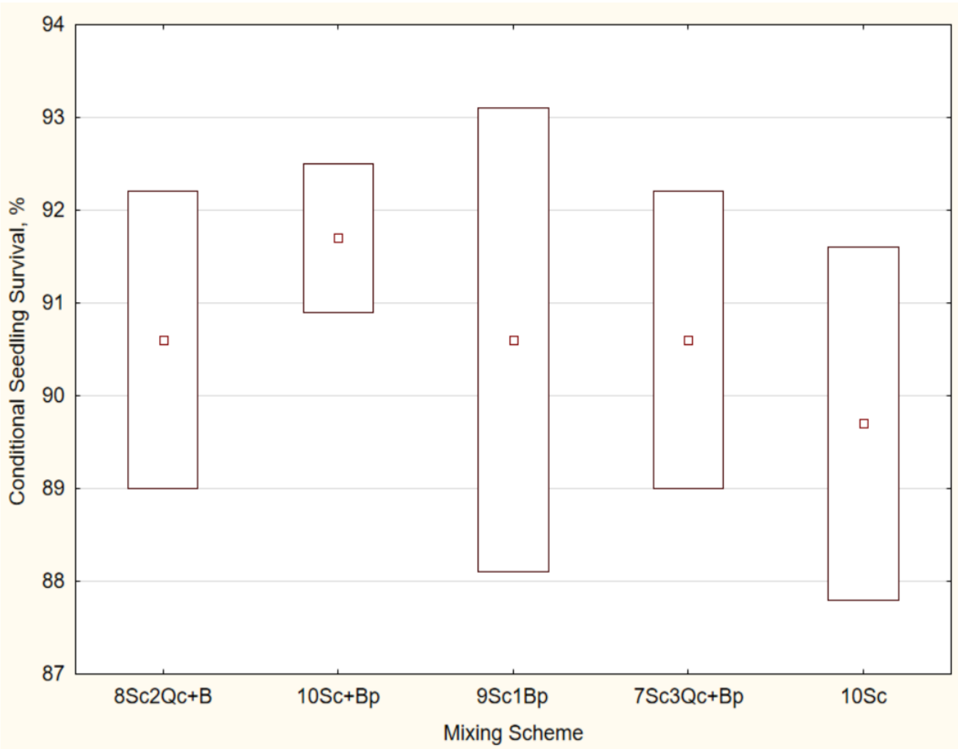

Figure 3. Dependence of the average survival rate of forest stands on the mixing scheme of the plantations

According to the data obtained, the F-ratio is equal to 0.48, and the corresponding p-value is 0.74. Since the obtained p-value (0.74) significantly exceeds the critical significance level of 0.05, it can be concluded that the difference in average survival rates among the studied mixing schemes is not statistically significant.

Table 3. Results of the analysis of variance (ANOVA) of the influence of mixing scheme on seedling survival

Sum of Squares - Effect	Degrees of Freedom (df) - Effect	Mean Square - Effect	Sum of Squares - Error (Residual)	Degrees of Freedom (df) - Error (Residual)	Mean Square - Error (Residual)	F-Ratio	p-value
Conditional Seedling Survival, %	6.04	4.00	1.51	31.24	3.12	0.48	0.74

Table 4 displays the key forest inventory indicators and growing conditions of five research sample plots established in artificial Scots pine stands. The age of the stands covers a wide range, from 39 to 57 years, which allows for the assessment of their development at various stages. The vast majority of plantations were created using the standard 2.5×0.5 m planting scheme, while the stands are characterized by high productivity and fullness indicators: timber stock ranges from 220 to 290 m^3 ha^{-1}, and fullness is between 0.7 and 0.9. It is worth noting that the research plots represent various forest growth condition types and mixing schemes, including both pure pine culture and complex mixed stands with admixtures of oak and birch, which ensures the representativeness of the sample for further analysis.

Table 4. Forest Inventory Characteristics and Growing Conditions of Research Sample Plots

Sample Plot No. (SP)	Age, years	Planting Scheme, m	Mixing Scheme	FGC	Fullness	Site Index (Bonitet)	Stock, m^3 ha^{-1}
1	39	2.5×0.5	8Sc2Qc+B	B3	0.9	I	220
2	57	2.5×0.7	10Sc+Bp	B2	0.7	II	290
3	45	2.5×0.5	9Sc1Bp	B2	0.8	I	280
4	48	2.5×0.5	7Sc3Qc+Bp	C2	0.9	I	260
5	55	2.5×0.6	10Sc	A2	0.7	II	250

The results of the forest inventory, presented in Table 5, illustrate the structural and sanitary condition of the forest stands on the research sample plots. According to the Kraft classification, the codominant layer (Class II) prevails in most stands, especially in pine, where its share ranges from 37.5% to 64.6% (SP No. 2 and No. 4, respectively). The share of suppressed, dying, and dead trees (Classes III, IV, and snags) is significant; for example, in pine on SP No. 2, it is about 50.0%, and in birch on SP No. 3, it is 85.7%, which indicates an active process of natural thinning at a mature age. Analysis of the sanitary condition confirms this trend: in some areas (e.g., SP No. 5, pine), the share of severely weakened and dying trees (Classes III, IV) is high (43.3%), whereas in birch on

SP No. 3, healthy trees (Class I) constitute 90.5%. This demonstrates that stability depends not only on the species but also on specific forest growth conditions and the mixing scheme.

Table 5. Distribution of Trees by Kraft Classes and Sanitary Condition, %

SP No.	Species	Kraft Classes, %	Sanitary Condition (Living Trees), %	Deadwood (Snags/Logs), %
		Dominant (I)	Codominant (II)	Suppressed (III, IV, Dead)
1	Sc	35.3	47.1	17.6
	Qc	14.3	42.9	42.8
	Bp	-	41.9	58.1
2	Sc	12.5	37.5	50.0
	Bp	-	28.6	71.4
3	Sc	22.6	50.9	26.5
	Bp	-	14.3	85.7
4	Sc	8.3	64.6	27.1
	Qc	26.9	30.1	43.8
	Bp	-	10.2	88.2
5	Sc	16.7	40.0	43.3

The analysis of variance (ANOVA) indicated that the influence of both the forest growth condition type (FGC) and the mixing scheme on seedling survival is statistically insignificant, despite the observed high average survival rates, with a tendency toward better results in fresh subors and mixed schemes. Concurrently, the forest inventory reveals a significant process of natural thinning in mature stands, where the proportion of suppressed and dying trees (Kraft Classes III, IV) can exceed 50% in some species, highlighting the necessity of controlling their sanitary condition.In the study by (Urgoiti Otazua and Paquette, 2018), it is proven that forest plantations are becoming crucial for providing society with both timber and non-timber products amidst a global reduction of natural forests. However, the predominance of monocultures can negatively impact ecosystem functions and reduce resilience to growing ecological threats. Thus, there is an urgent need for mixed-species stands, which, by supporting biodiversity and different recovery mechanisms, ensure greater resistance, adaptive capacity, and stability of productivity compared to monocultures. Based on the review by (Nguyen *et al.*, 2018), recent studies confirm the functional advantages of mixed plantations over traditional monocultures, although practical guidelines for their design and management remain insufficient. Mixed systems have been found to improve productivity and ecosystem services, but full implementation requires additional research into economic feasibility, the development of adapted silvicultural guidelines for various socio-economic conditions, and the assessment of their resistance to pests and disturbances at a mature age. The research by (Blystiv *et al.*, 2021), focused on stand stability, tested a methodology based on calculating stability indicators (stability coefficient, loss of biotic/ecological stability) using forest inventory assessment, sanitary condition, and natural regeneration, allowing stands to be classified as stable, conditionally stable, or unstable. The resulting indicators (particularly the living space tension indicator) are crucial for planning forestry measures in breeding facilities, including forest genetic reserves and permanent forest seed plots. The study by (Puzrina *et al.*, 2022) confirms the relevance of the pine stand dieback problem in Ukraine, revealing that the main pathological cause is infection by the pathogen Heterobasidion annosum, combined with mass infestation by stem pests, predominantly bark beetles of the genus Tomicus. The dynamics of observations since 2011 show a deterioration in the sanitary condition of pine stands, especially after the dry growing seasons of 2015-2017, which led to an outbreak of aggressive bark beetle species (Ips acuminatus); however, since 2019, a decrease in their numbers has been observed due to climatic factors (increased precipitation and decreased temperature). The results obtained serve as a basis for developing a strategy for managing damaged forest areas.

The results obtained indicate a relatively high level of survival of forest crops under the studied conditions, however, the differences found between individual options were not always statistically significant at the accepted level of significance. This may be due to the limited number of trial plots, intra-plot spatial heterogeneity, and the influence of abiotic and biotic factors that are difficult to fully control in field conditions. At the same time, from an ecological and silvicultural point of view, even statistically insignificant differences in survival are of practical importance, since they affect the initial density of stands, competitive relationships, and subsequent stability of forest crops. These limitations necessitate cautious interpretation of the results and indicate the feasibility of further studies with an expanded sample and longer monitoring.

CONCLUSIONS

The analysis established a high, yet statistically insignificant, influence of both the forest growth condition type and the mixing scheme on seedling survival, indicating the consistently high effectiveness of traditional forest regeneration methods under the studied conditions, irrespective of minor variations in FGC and composition. Simultaneously, the inventory of mature stands revealed a significant process of natural thinning and deterioration of the sanitary condition, where the proportion of suppressed and dying trees reaches up to 85.7% for birch and 50% for pine. These results, consistent with current global trends, confirm that while initial survival is high, the long-term stability of stands against external factors remains a critical issue. Therefore, future silvicultural measures should be directed not so much at increasing initial survival but at developing adapted guidelines for managing mature mixed stands that ensure increased biotic and ecological stability in the face of growing climatic risks.

Forestry recommendations.

1. Orientation of silvicultural measures to the long-term stability of plantations. Given the high initial survival rate of seedlings, further silvicultural

measures should be directed not to intensifying the stage of crop creation, but to ensuring their stable development in the middle and old age periods by regulating the density and species composition.

2. Optimization of maintenance and thinning regimes. It is recommended to carry out the first maintenance felling during the period of crown closure in order to reduce intraspecific and interspecific competition. Further thinning should be carried out in a differentiated manner, taking into account the sanitary condition of trees and the spatial structure of plantations, giving preference to the removal of depressed and weakened individuals.

3. Adjustment of the composition of mixed plantations. According to the results of the research, it is advisable to maintain mixed stands with the dominance of the main species (pine) and the participation of related deciduous species within limits that do not lead to excessive competition at later stages of development. Particular attention should be paid to regulating the participation of fast-growing deciduous species, which in mature cultures demonstrate a high level of suppression and drying.

4. Systematic monitoring of the sanitary condition. It is recommended to implement regular monitoring of the condition of stands with recording indicators of viability, the level of suppression and manifestations of drying, which will allow timely adjustment of silvicultural measures and reduce the risks of degradation of stands.

5. Adaptation of forestry decisions to climate change. When planning maintenance activities, it is advisable to take into account the increase in climatic risks, in particular the frequency of dry periods, by reducing excessive density of plantings and maintaining structural diversity, which will contribute to increasing their biotic and ecological resilience.

Further research should focus on long-term monitoring of forest crops with an assessment of the dynamics of their growth, condition and structure in different age periods. The priority area is the study of the resistance of stands to abiotic and biotic disturbances, in particular droughts, temperature extremes and damage by pests. Special attention should be paid to the analysis of the dynamics of mixed stands with different ratios of tree species, which will allow assessing their potential for increasing ecological stability and productivity in the conditions of the North-Eastern Forest-Steppe of Ukraine.

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