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Productivity of modal forest stands in Ukrainian Polissia depending on the compliance of the main tree species with the native forest type

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Abstract. The study aimed to assess the composition and mensurational characteristics of near-native and secondary forest stands, compare their mean annual increment with native references, and clarify natural productivity patterns across site conditions. The analysis was based on forest inventory data combined with geoinformation resources. Productivity was assessed by comparing mean increment values and ranking natural productivity scores. The average species composition of compositionally near-native modal stands differed from that of the reference native stands across most forest-site types. In poor and fairly poor site conditions, a higher share of silver birch (*Betula pendula* Roth) was observed; in fairly rich site conditions, higher proportions of birch (*B. pendula*) and European hornbeam (*Carpinus betulus* L.); and in rich site conditions, a suite of native hard- and soft-broadleaved species. Secondary stands showed the following patterns: in poor site conditions they were dominated by jack pine (*Pinus banksiana* Lamb.) and birch (*B. pendula*); in fairly poor and fairly rich site conditions by birch (*B. pendula*); and in rich site conditions by hornbeam (*C. betulus*), northern red oak (*Quercus rubra* L.), Scots pine (*Pinus sylvestris* L.), black alder (*Alnus glutinosa* (L.) Gaertn.), and birch (*B. pendula*). The mean increment of modal Scots pine stands exceeded native references by 17-58% in poor site conditions and by 2-48% in fairly poor site conditions, depending on the soil moisture regime, whereas in fairly rich site conditions, modal stands close in composition to native forests fell short by 19-37%, while in rich site conditions the increments were similar. In the most widespread site types in poor, fairly poor, and fairly rich site conditions, modal native stands were more productive than

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secondary ones; in rich site conditions, however, secondary stands prevailed by 13-16%. The productivity scores of modal stands differed substantially from those of the native reference scales: they were higher in poor and fairly poor site conditions but lower in rich site conditions. The highest natural productivity scores of secondary stands were recorded in fresh and moist rich site conditions and in fresh fairly poor site conditions. The obtained results provided a scientific basis for refining the scales of natural productivity and for typology-based planning of silvicultural measures

Keywords: forest site conditions; mean annual increment; tree species composition; secondary forest stand; native reference stands; productivity assessment scale

INTRODUCTION

The assessment of forest productivity in relation to stand composition and site conditions has acquired growing importance in light of climate change and the intensification of forest use. The productivity of native and secondary forest stands is a key indicator of ecosystem stability, carbon sequestration, and the efficiency of forest management strategies. In Ukrainian Polissia, where natural and post-disturbance stands coexist across diverse forest-site conditions, understanding how species composition and stand origin influence productivity remains a priority for sustainable forestry planning. The research of H. Pretzsch *et al.* (2023) showed that forest growth in Europe demonstrates divergent regional trends, largely due to climate-induced disturbances such as droughts and heatwaves, which significantly alter biomass accumulation patterns. These findings emphasise the need to investigate productivity not only by ecological region but also within typological frameworks reflecting site quality and stand composition.

Numerous studies have underlined that the stability and level of forest productivity are closely linked to the biological and structural diversity of stands. M. del Río *et al.* (2022) found that the mixture of two or more tree species increases resistance to interannual climate variability, contributing to more stable productivity. T. Hilmers *et al.* (2024) further demonstrated that structural diversity modifies crown biomass allocation and enhances growth efficiency, promoting resource-efficient and climate-resilient forests. Similarly, T. Wang *et al.* (2024) confirmed that stand structure plays a more decisive role in sustaining productivity stability than species diversity alone, highlighting that optimal canopy stratification and age heterogeneity are crucial for maintaining increment under changing environmental conditions. Climatic sensitivity varies considerably among tree species typical for Polissia. Research by P. Dukat *et al.* (2023) revealed that Scots pine (*Pinus sylvestris* L.) exhibits a pronounced physiological response to drought, manifested in reduced sap flow and photosynthetic activity, which directly limits its increment potential in poor site conditions. In contrast, *Ā. Jansons et al.* (2025) demonstrated that older hemiboreal stands, particularly those dominated by broadleaved species, retain higher carbon storage and long-term productivity, although they grow more slowly than secondary pine or birch forests. These conclusions support the principle that natural or near-natural stands provide greater ecological stability and contribute more effectively to carbon balance maintenance. At the policy level, the State Forest Resources Agency of Ukraine (2025) emphasised the gradual implementation of close-to-nature silvicultural approaches, reduction of reconstruction fellings, and greater reliance on natural regeneration processes. This reflects a broader shift in forest management philosophy from a raw-material focus to a multifunctional ecological framework.

Therefore, the scientific community increasingly recognises that the assessment of forest productivity must integrate ecological typology, site conditions, and stand origin. Comparative evaluation of native, near-native, and secondary formations provides a robust basis for refining natural productivity scales and guiding adaptive silvicultural strategies in Polissia. The aim of the research is to evaluate the average composition and average mensurational indicators (age, stock volume, increment) of compositionally close to native and secondary forest stands, to compare their mean annual increment with native reference stands, and to refine the scale of natural productivity across forest site conditions.

LITERATURE REVIEW

Forest stand productivity is one of the key indicators of the ecological and economic functionality of forest ecosystems, as well as an important measure of their long-term capacity to accumulate biomass and carbon. Within Ukrainian Polissia, traditionally characterized by a cold-humid climate, widespread pine forests, podzolic soils, and extensive coniferous and mixed forest areas, contemporary climatic and anthropogenic drivers may significantly alter the spatiotemporal dynamics of productivity (Snizhko *et al.,* 2024). When analyzing productivity and stability, it is essential to distinguish stand origin. In national forestry and mensurational practice, *native stands* are defined as those formed under minimal anthropogenic disturbance, with natural succession and a typical valuable species composition characteristic of specific forest formations. In contrast, *secondary stands* emerge following major disturbances (clear-cutting, fire, drainage, or changes in groundwater

regime) and are often represented by fast-growing or secondary species combinations, modified in taxonomic and structural composition (Tkach *et al.*, 2024). According to national estimates, the area of secondary stands in lowland Ukraine reaches about 400,000 ha, with nearly 48% located in Polissia. In Polissia, stand origin directly affects the level and stability of productivity: empirical field studies indicate that mixed and partially restored stands (e.g., pine–birch combinations) may demonstrate higher bioproductivity compared with pure modal pine stands, though with a different sensitivity profile to fire risk or water deficit. To enhance structural stability and increase productivity in young secondary stands, close-to-nature silviculture is effective. This approach maximizes site potential by applying complex regeneration harvests in combination with measures that support natural regeneration of native species (Zhezhkun *et al.,* 2023). Ukrainian researchers emphasize that the foundation for increasing forest productivity should be the differentiation of forest management systems and silvicultural measures on a zonal-typological basis.

The forest cenoses of Ukrainian Polissia, depending on site type, are dominated by Scots pine (*Pinus sylvestris* L.), silver birch (*Betula pendula* Roth), pedunculate oak (*Quercus robur* L.), black alder (*Alnus glutinosa* (L.) Gaertn.), and aspen (*Populus tremula* L.). Scots pine (*P. sylvestris*), common in northern temperate latitudes, traditionally exhibits high plasticity regarding soil-moisture regimes and often ensures stable primary increment on the poor sandy soils of Polissia. However, its productivity is strongly constrained under extreme events, as droughts can significantly reduce increment and regeneration. This is confirmed by regional and interregional analyses of pine responses to climatic drivers and previous growth status (Mikalajūnas *et al.*, 2021). On poor and dry sites, pine stands often outperform more demanding species, but their sensitivity to frequent extremes (drought-induced dieback, windthrow, or pest outbreaks following stress) makes long-term stability of productivity vulnerable. Oak stands (*Q. robur* and *Q. petraea*) are characterized by slower initial growth, but under favorable soil and nutrient conditions, they form high long-term productivity and stable biomass stocks (Uhl *et al.*, 2022; Cerný *et al.*, 2024). Recent studies show that mixing oak with other species (particularly pine) may partly compensate for productivity losses under climate change, though the effects depend strongly on soil quality and local microclimatic conditions (Vospernik *et al.*, 2024). Oak forests provide more stable long-term carbon sequestration potential compared with secondary stands of fast-growing species, although their early productivity is often lower. Management interventions (site selection, species mixtures) are therefore crucial for enhancing total productivity in young stands (Sabatini *et al.*, 2019).

Birch (*B. pendula*) and aspen (*P. tremula*) are typical early successional species colonizing disturbed areas. They rapidly occupy open space, accelerate biomass accumulation, and improve soil fertility in the early stages of recovery. However, in the mid- to long-term, their productivity often falls short of target stands due to lower long-term carbon accumulation and faster dieback of groups under natural thinning (Martiník *et al.*, 2024). New modeling approaches and the development of site-index systems for birch have improved the ability to predict its productivity across different soils (Lee *et al.*, 2024). As pioneer species, birch and aspen enhance early cumulative productivity and support reclamation and soil improvement, but their long-term contribution to timber reserves and stability is limited. Thus, their optimal role is temporary within restoration systems or as components of mixed stands (Tullus *et al.*, 2025).

Black alder (*A. glutinosa*) is an important tree species that plays a key role in restoring degraded lands, particularly in Ukrainian Polissia (Lukyanets *et al.*, 2022). Its capacity for rapid growth, efficient nitrogen fixation, and soil-improving properties makes it promising for forestry (Anadon-Rosell *et al.*, 2022). Black alder thrives on moist soils, including floodplains, where its productivity can reach 10-15 $m^3 \cdot ha^{-1} \cdot yr^{-1}$ depending on water regime and soil fertility. In mixed stands of black alder with other species such as willow (*Salix*), total biomass accumulation increases. For example, studies in Croatia revealed that alder–willow mixtures produced greater total biomass than alder monocultures (Bogdan *et al.*, 2017), highlighting the positive effect of species coexistence in enhancing productivity and ecosystem stability. In general, forest productivity in Ukrainian Polissia depends on the interaction between climate, site conditions, and species composition. Scots pine dominates poor soils but is vulnerable to drought stress, while oak and black alder provide higher long-term productivity and carbon storage on richer sites. Birch and aspen enhance early biomass accumulation but have limited long-term potential. Mixed and near-natural stands offer greater stability and efficiency, confirming the importance of close-to-nature and typology-based management for sustaining productivity across diverse forest conditions.

MATERIALS AND METHODS

The database of the production association Ukrderzhlisproekt (n.d.) served as the primary source of data for the analysis. The general population of forest-covered plots belonging to the structural subdivisions of the the State Specialized Forest Enterprise Forests of Ukraine (n.d.) that territorially fall within Ukrainian Polissia includes: parts of Volyn, Rivne, Khmelnytskyi, Zhytomyr, Kyiv, Chernihiv, and Sumy regions. A geospatial analysis was conducted using data from the Ukrainian Research Institute of Forestry and Agroforestry (n.d.)

and the State Forest Fund of Ukraine (2025), which made it possible to establish the territorial affiliation of the forest fund of the forestry divisions of the Northern Forestry Enterprise, Polissya Forestry, Stolychny Forestry, and Podillya Forestry to the Ukrainian Polissya region. The query and analysis were conducted using the Lisovporiadnyk software in two stages for each forest site type (Aleksiiuk *et al.*, 2019). At the first stage, the average tree species composition of native (including those close to and distant from the reference native structure) and secondary stands was determined for each forest type. The correspondence of the main tree species to the native species of a given forest type was determined programmatically by using the query "native species of the forest type" in the "Derived Indicators" section. Stands where the main species matched the native species of the forest type were classified as native; otherwise, they were classified as secondary. At the second stage, the average mensurational indicators of modal stands - both those corresponding and not corresponding to the main species of native stands of a given forest type - were calculated for the most widespread forest site conditions.

The average tree species composition was determined as the ratio of cumulative growing stock of component species using the query in the "Characteristics of Tree Species Components" section, following the standard forest inventory methodology (Ukrderzhlisproekt, n.d.). The average age and average volume stock per hectare were determined programmatically: average age was calculated as a weighted mean of the main species values across compartments, and average growing stock per hectare was obtained as a weighted mean of the cumulative values of the first and second canopy layers of each stand unit. The mean annual increment (MAI) was calculated as the ratio of the average growing stock per hectare to the average age. The basic unit of analysis was the forest subcompartment. The sample sizes of stands across forest site types were as follows: A_0 – 0.1 thousand subcompartments, A_1 (n.d.) 14.8 thousand, A_2 (n.d.) 90.6 thousand, A_3 (n.d.) 11.2 thousand, A_4 (n.d.) 6.3 thousand, A_5 (n.d.) 7.1 thousand, B_1 (n.d.) 1.9 thousand, B_2 (n.d.) 247.1 thousand, B_3 (n.d.) 196.6 thousand, B_4 (n.d.) 65.7 thousand, B_5 (n.d.) 16.9 thousand, C_2 (n.d.) 99.0 thousand, C_3 (n.d.) 133.5 thousand, C_4 (n.d.) 89.0 thousand, C_5 (n.d.) 9.8 thousand, D_2 (n.d.) 16.5 thousand, D_3 (n.d.) 11.1 thousand, D_4 (n.d.) 1.9 thousand, and D_5 (n.d.) 0.1 thousand. The assessment scale of natural productivity by forest site conditions was developed through ranking productivity scores separately for native and secondary stands (Turkevych *et al.*, 1973). Productivity scores were defined by ranking MAI values for native and secondary stands independently. Comparisons of productivity between native and secondary stands across forest site conditions were made based on MAI indicators.

RESULTS AND DISCUSSION

Based on the analysis of forest inventory data from more than 130,000 subcompartments within Ukrainian Polissia, it was established that in poor site conditions, the most productive stands are modal Scots pine forests in fresh and moist sites, where the MAI per hectare exceeds 4 m^3 (Table 1).

***Table 1**. Average mensurational characteristics of modal stands corresponding to the main species of forest types in poor site conditions*

Forest site conditions	Tree species composition	Mean age, years	Mean stand volume, $m^3 \cdot ha^{-1}$	Mean annual increment (MAI), $m^3 \cdot ha^{-1}$
A_0	100% -Scots pine	50	43	0.86
A_1	100% –Scots pine, <5% (n.d.) silver birch	50	134	2.68
A_2	100% –Scots pine, <5% (n.d.) silver birch	47	200	4.26
A_3	90% –Scots pine, 10% (n.d.) silver birch	46	186	4.04
A_4	90% –Scots pine, 10% (n.d.) silver birch	50	137	2.74
A_5	90% –Scots pine, 10% (n.d.) silver birch	70	100	1.43

***Source:** developed by the authors*

It should be noted that, compared with the data in Table 1, average tree species composition of modal stands in fresh and moist poor site conditions of Ukrainian Polissia, according to V. Tkach *et al.* (2024), reveals a relatively lower proportion of silver birch: occurring sporadically in fresh sites and up to 5% in moist sites. In comparison with findings reported by researchers I. Turkevych *et al.* (1973) half a century ago, who also confirmed the highest productivity of native reference Scots pine stands in these site conditions, the MAI per unit area of modal stands is now 17% higher in A_2 and as much as 47% higher in A_3. It is also worth noting the comparatively higher MAI of modal Scots pine stands in other forest site conditions: 27% higher in A_1, 58% in A_4, and 55% in A_5.

The productivity of secondary stands in dry poor site conditions is lower compared with modal Scots pine (*P. sylvestris* L.) stands, with MAI reduced by 9%. Secondary stands are also less productive in fresh and moist poor site conditions, where their increment falls short of modal stands by 9% and 21%, respectively. Conversely, in very dry and very wet poor site

conditions, secondary stands demonstrate higher MAI: in A_0 by 33% and in A_5 by 51% (Tables 1-2). The tree species composition of secondary stands in dry and very dry poor site conditions is dominated mainly by jack pine (*Pinus banksiana* Lamb.), whereas in other site conditions silver birch (*B. pendula* Roth) prevails.

***Table 2**. Average mensurational characteristics of secondary forest stands in poor site conditions*

Forest site conditions	Tree species composition	Mean age, years	Mean stand volume, $m^3 \cdot ha^{-1}$	Mean annual increment (MAI), $m^3 \cdot ha^{-1}$
A_0	60% – jack pine, 40% (n.d.) Scots pine	53	68	1.28
A_1	50% – jack pine, 30% (n.d.) silver birch, 20% (n.d.) Scots pine, <5% (n.d.) Crimean pine (*Pinus nigra* subsp. *pallasiana*)	45	110	2.44
A_2	70% (n.d.) silver birch, 10% (n.d.) Scots pine, 10% – jack pine, 10% – black locust *(Robinia pseudoacacia L.)*. <5% (n.d.) Crimean pine	40	155	3.88
A_3	80% (n.d.) silver birch, 10% (n.d.) Scots pine, 10% – European aspen	38	122	3.21
A_4	90% (n.d.) silver birch, 10% (n.d.) Scots pine, <5% (n.d.) European aspen, black alder	33	92	2.79
A_5	80% (n.d.) silver birch, 20% (n.d.) Scots pine, <5% (n.d.) European aspen, black alder	37	107	2.89

***Source:** developed by the authors*

According to long-term studies in Northern and Eastern European countries, the MAI of Scots pine (*P. sylvestris* L.) on poor sandy soils ranges from 4 to 6 $m^3 \cdot ha^{-1} \cdot yr^{-1}$ (Varnagiryte-Kabašinskienė *et al.*, 2015). Ukrainian studies demonstrate similar productivity values for modal stands in poor site conditions. The MAI of modal stands corresponding to the main species of the native forest type in fairly poor site conditions, based on current forest inventory data, demonstrates higher productivity compared with native reference Scots pine stands (Turkevych *et al.*, 1973). In dry fairly poor site conditions, the MAI was 32% higher; in fresh fairly poor site conditions (n.d.) 7% higher; in moist site conditions (n.d.) 2% higher; in wet site conditions (n.d.) 42% higher; and in very wet site conditions (n.d.) 48% higher. With regard to productivity across moisture regimes, the most productive forest site conditions are fresh sites, whereas the least productive are very wet sites (Table 3).

***Table 3**. Average mensurational characteristics of modal stands corresponding to the main species of forest types in fairly poor site conditions*

Forest site conditions	Tree species composition	Mean age, years	Mean stand volume, $m^3 \cdot ha^{-1}$	Mean annual increment (MAI), $m^3 \cdot ha^{-1}$
B_1	100% -Scots pine, <5% (n.d.) silver birch	50	199	3.98
B_2	90% -Scots pine, 10% - silver birch, <5% (n.d.) pedunculate oak	51	268	5.25
B_3	90% -Scots pine, 10% - silver birch, <5% (n.d.) pedunculate oak, black alder	51	236	4.63
B_4	80% -Scots pine, 20% - silver birch, <5% (n.d.)black alder	48	172	3.58
B_5	80% -Scots pine, 20% - silver birch, <5% (n.d.)black alder	63	131	2.08

***Source:** developed by the authors*

The tree species composition of modal stands corresponding to the main species of forest types in fresh, moist, wet, and very wet fairly poor site conditions differs somewhat from the data reported by V. Tkach *et al.* (2024). In fresh fairly poor site conditions, a higher proportion of silver birch (*B. pendula* Roth) and pedunculate oak (*Q. robur* .) was observed; in moist sites, black alder (*A. glutinosa* (L.) Gaertn.) appeared in the composition; while in wet and very wet sites, silver birch (*B. pendula* Roth) was markedly more abundant along with the presence of black alder (*A. glutinosa* (L.) Gaertn.). In the composition of secondary stands in fairly poor site conditions, silver birch (*B. pendula* Roth) predominates. The MAI of secondary stands in most moisture regimes, except for very wet sites, is lower than that of modal Scots pine stands by 7-21% (Table 4). In very wet sites, however, secondary birch stands exhibit a higher MAI, exceeding that of modal Scots pine stands by 11%.

***Table 4**. Average mensurational characteristics of secondary forest stands in fairly poor site conditions*

Forest site conditions	Tree species composition	Mean age, years	Mean stand volume, $m^3 \cdot ha^{-1}$	Mean annual increment (MAI), $m^3 \cdot ha^{-1}$
B_1	40% – silver birch, 30% – Scots pine, 20% (n.d.) pedunculate oak, 10 % – Norway spruce (*Picea abies* (L.) H. Karst.) <5% (n.d.) black locust	42	139	3.31
B_2	70% – silver birch, 10% – Scots pine, 10% (n.d.) pedunculate oak, 10% – European aspen, <5% (n.d.) black locust, Norway spruce	45	195	4.33
B_3	60% – silver birch, 10% – Scots pine, 10% (n.d.) pedunculate oak, 10 % – European aspen, 10 % – black alder, <5% (n.d.) Norway spruce	47	171	3.64
B_4	70% – silver birch, 10% – Scots pine, 10 % – black alder, 10 % – European aspen	38	127	3.34
B_5	80% – silver birch, 10% -Scots pine, 10 % – black alder, <5% (n.d.) European aspen	46	108	2.35

***Source:** developed by the authors*

According to studies conducted in Lithuania by E. Linkevičius *et al.* (2023), the MAI of Scots pine (*P. sylvestris* L.) on sandy loam soils is approximately 5.2 $m^3 \cdot ha^{-1} \cdot yr^{-1}$. Silver birch (*B. pendula* Roth) also demonstrates high productivity under fairly poor site conditions. In comparison, data obtained in Ukraine indicate that the MAI of Scots pine on sandy loam soils is about 4.5 $m^3 \cdot ha^{-1} \cdot yr^{-1}$, while that of silver birch is 5.0 $m^3 \cdot ha^{-1} \cdot yr^{-1}$. These values highlight certain differences in productivity across Central Europe (Martiník *et al.*, 2018).

In fairly rich site conditions of Ukrainian Polissia, dry moisture regimes are atypical. Native stands in fresh and moist fairly rich site conditions are generally complex in structure, with Scots pine (*P. sylvestris*) prevailing in the upper canopy layer and European hornbeam (*Carpinus betulus* L.) dominating the lower layer. In wet and very wet fairly rich site conditions, black alder (*A. glutinosa* (L.) Gaertn.) is typically the dominant species. The composition of modal stands corresponding to the main species of forest types in fresh and wet fairly rich site conditions differs somewhat from the findings of V. Tkach *et al.* (2024): in fresh sites, a higher share of silver birch (*B. pendula*) occurs in the upper canopy layer and a lower share of hornbeam (*C. betulus*) in the lower layer, while in wet sites, silver birch (*B. pendula*) accounts for a substantially greater proportion. The average mensurational characteristics of modal stands corresponding to the main species of forest types in fairly rich site conditions are presented in Table 5.

***Table 5**. Average mensurational characteristics of modal stands corresponding to the main species of forest types in fairly rich site conditions*

Forest site conditions	Tree species composition 1st canopy layer / 2nd canopy layer	Mean age, years	Mean stand volume, $m^3 \cdot ha^{-1}$	Mean annual increment (MAI), $m^3 \cdot ha^{-1}$
C_2	70% – Scots pine, 20% (n.d.) pedunculate oak, 10% – silver birch, <5% (n.d.) European hornbeam, European aspen / 70% – European hornbeam, 10% – Norway spruce, 10% (n.d.) pedunculate oak, 10% – Scots pine, <5% (n.d.) silver birch, small-leaved lime (*Tilia cordata* Mill.), Norway maple (*Acer platanoides* L.)	55	273	4.96
C_3	50% – Scots pine, 30% (n.d.) pedunculate oak, 10% – silver birch, 10% – black alder, <5% (n.d.) European hornbeam, European aspen, Norway spruce / 70% – European hornbeam, 20% (n.d.) pedunculate oak, 10% – Norway spruce, <5% (n.d.) silver birch, Scots pine, small-leaved lime	52	218	4.19
C_4	80% – black alder, 20% – silver birch, <5% (n.d.) Scots pine, European aspen, pedunculate oak	45	169	3.76
C_5	80% – black alder, 20% – silver birch, <5% (n.d.) Scots pine, European aspen	51	154	3.02

***Source:** developed by the authors*

The highest values of MAI in modal stands corresponding to the main species of forest types were recorded in fresh and moist fairly rich site conditions. The MAI of modal stands corresponding to the main species of forest types is lower in all fairly rich site conditions than in native reference stands: in fresh sites by

30%, in moist sites by 37%, in wet sites by 19%, and in very wet sites by 26%. In tree species composition of secondary stands, pedunculate oak (*Q. robur* .) is most common in fresh fairly rich site conditions, while silver birch (*B. pendula* Roth) dominates in more humid site conditions (Table 6). The MAI of secondary stands across all mesic site types is lower compared with modal stands corresponding to the main species of fairly rich site conditions: in fresh sites by 20%, in moist sites by 8%, in wet sites by 4%, and in very wet sites by 11%.

***Table 6**. Average mensurational characteristics of secondary forest stands in fairly rich site conditions*

Forest site conditions	Tree species composition 1st canopy layer / 2nd canopy layer	Mean age, years	Mean stand volume, $m^3 \cdot ha^{-1}$	Mean annual increment (MAI), $m^3 \cdot ha^{-1}$
C_2	40% (n.d.) pedunculate oak, 20% – silver birch, 20% –Scots pine, 10% – European hornbeam, 10% – European aspen, <5% (n.d.) Norway spruce, northern red oak (*Quercus rubra* L.), black alder / 80% – European hornbeam, 10% – Norway spruce, 10% (n.d.) pedunculate oak, <5% (n.d.) Scots pine, Norway maple	53	211	3.98
C_3	40% – silver birch, 20% (n.d.) pedunculate oak, 10% – black alder, 10% – European aspen, 10% –Scots pine, 10% – European hornbeam, <5% (n.d.) Norway spruce, northern red oak, European ash (*Fraxinus excelsior* L.) / 80% – European hornbeam, 10% – pedunculate oak, 10% – silver birch, <5% (n.d.)Norway maple, small-leaved lime	51	196	3.84
C_4	60% – silver birch, 20% – black alder, 10% – European aspen, 10% – Scots pine, <5% (n.d.)pedunculate oak, Norway spruce, white willow (*Salix alba* L.)	41	148	3.61
C_5	70% – silver birch, 20% – black alder, 10% – European aspen, <5% (n.d.) Scots pine, white willow	50	134	2.68

***Source:** developed by the authors*

According to A. Terentiev *et al.* (2023), the MAI of Scots pine (*P. sylvestris* L.) on loamy soils varies from 5 to 8 $m^3 \cdot ha^{-1} \cdot yr^{-1}$ at the age of 60-80 years. These values may change depending on specific site conditions, particularly humus content and soil moisture (Aldea *et al.*, 2021). The MAI of pedunculate oak (*Q. robur* .) on loamy soils is approximately 4-6 $m^3 \cdot ha^{-1} \cdot yr^{-1}$ at the age of 80-100 years (Kazimirović *et al.*, 2024). Compared with other species, silver birch (*B. pendula* Roth) demonstrates faster growth in fairly rich site conditions. The MAI of black alder (*A. glutinosa* (L.) Gaertn.) on loamy soils reaches about 6-8 $m^3 \cdot ha^{-1} \cdot yr^{-1}$ at the age of 50-70 years. Alder is especially productive at a young age. Rich site conditions are comparatively the least represented in Ukrainian Polissia, dry sites are absent altogether in the region. In the tree species composition of modal stands corresponding to the main species of forest types in fresh and moist rich site conditions, pedunculate oak (*Q. robur*) typically dominates the upper canopy layer, accounting for 30-40% of the total volume, while hornbeam (*C. betulus* L.) dominates the lower canopy. In wet and very wet rich site conditions, black alder (*A. glutinosa*) prevails in simple-structured stands (Table 7).

***Table 7**. Average mensurational characteristics of modal stands corresponding to the main species of forest types in rich site conditions*

Forest site conditions	Tree species composition 1st canopy layer / 2nd canopy layer	Mean age, years	Mean stand volume, $m^3 \cdot ha^{-1}$	Mean annual increment (MAI), $m^3 \cdot ha^{-1}$
D_2	40% (n.d.) pedunculate oak, 10% – European hornbeam, 10% – European aspen, 10% – silver birch, 10% – European ash, 10% – Norway maple, 10% – small-leaved lime, <5% (n.d.) Norway spruce, Scots pine/ 70% – European hornbeam, 20% – Norway spruce, 10% (n.d.) Norway maple, <5% (n.d.) small-leaved lime	53	202	3.81
D_3	30% (n.d.) pedunculate oak, 10% – European hornbeam, 10% – European aspen, 10% – silver birch, 10% – European ash, 10% – Norway maple, 10% – small-leaved lime, 10% – black alder, <5% (n.d.) Norway spruce / 70% – European hornbeam, 20% – Norway spruce, 10% (n.d.) Norway maple, <5% (n.d.) small-leaved lime	54	204	3.78
D_4	70% – black alder, 10% pedunculate oak, 10% – silver birch, 10% – European ash, <5% (n.d.) European aspen, small-leaved lime, European hornbeam	47	179	3.81
D_5	90% – black alder, 10% – silver birch, <5% (n.d.) European ash, white willow	54	172	3.19

***Source:** developed by the authors*

The tree species composition of modal stands corresponding to the main species of forest types in fresh and wet rich site conditions differs substantially from the data of V. Tkach *et al.* (2024), showing greater species diversity and a lower share of the main species (n.d.) pedunculate oak (*Q. robur* .) and black alder (*A. glutinosa* (L.) Gaertn.). The MAI of modal stands corresponding to the main species of forest types does not vary significantly among fresh, moist, and wet rich site conditions. Native reference stands of rich site conditions demonstrate considerably higher increments, with the highest productivity recorded in moist rich site conditions. Based on current forest inventory data, the MAI of modal stands corresponding to the main species is lower than that of native reference stands by nearly 41% in fresh sites, by 51% in moist sites, by 30% in wet sites, and by 45% in very wet sites. Regional studies have shown that the optimal productivity range of oak stands in Polissia is between 5 and 12 $m^3 \cdot ha^{-1} \cdot yr^{-1}$ depending on age and site index. The highest increments are reached in intermediate-aged stands (~35 years), after which current increment stabilizes or slightly declines.

In the tree species composition of secondary stands, hornbeam (*C. betulus* L.) dominates in fresh and moist rich site conditions, black alder (*A. glutinosa*) in wet sites, and silver birch (*B. pendula* Roth) in very wet sites (Table 8). The productivity of secondary stands compared with modal stands corresponding to the main species of forest types is higher in all moisture regimes of rich site conditions except wet ones. In fresh rich site conditions, the MAI of secondary stands exceeds that of modal stands by 16%, in moist sites by 13%, and in very wet sites by 14%.

***Table 8**. Average mensurational characteristics of secondary forest stands in rich site conditions*

Forest site conditions	Tree species composition 1st canopy layer / 2nd canopy layer	Mean age, years	Mean stand volume, $m^3 \cdot ha^{-1}$	Mean annual increment (MAI), $m^3 \cdot ha^{-1}$
D2	20% – European hornbeam, 20% – northern red oak, 20% – Scots pine, 10% (n.d.) pedunculate oak, 10% – silver birch, 10% – European ash, 10% – European aspen, <5% (n.d.) Norway spruce, small-leaved lime / 70% – European hornbeam, 20% – Norway maple, 10% – Norway spruce, <5% (n.d.) small-leaved lime	48	217	4.52
D3	20% – European hornbeam, 10% – northern red oak, 10% – Scots pine, 10% (n.d.) pedunculate oak, 10% – silver birch, 10% – European ash, 10% – European aspen, 10% – black alder, 10% – small-leaved lime, <5% (n.d.) Norway spruce / 50% – European hornbeam, 20% – Norway maple, 20% – Norway spruce, 10% (n.d.) pedunculate oak, <5% (n.d.) small-leaved lime	51	222	4.35
D4	40% – black alder, 20% – European ash, 20% – silver birch, 10% – pedunculate oak, 10% – European aspen, <5% (n.d.) European hornbeam, small-leaved lime	48	177	3.69
D5	40% – silver birch, 20% – black alder, 20% – white willow, 10% – Scots pine, <5% (n.d.) European aspen	58	215	3.71

***Source:** developed by the authors*

Local studies indicate that in Ukrainian Polissia hornbeam (*C. betulus* L.) is characterised by relatively high mean increment values on fertile soils in middle-aged stands; however, its productivity declines markedly with age. This defines its role as an accompanying rather than a main species in the highly productive oak forests of the region. Northern red oak (*Q. rubra* L.) in Europe and North America shows high growth rates on fertile soils. Typical MAI values range between 7 and 12 $m^3 \cdot ha^{-1} \cdot yr^{-1}$ in middle-aged stands (40-90 years), with peak values exceeding 12 $m^3 \cdot ha^{-1} \cdot yr^{-1}$ on particularly nutrient-rich sites under proper tending regimes (Nicolescu *et al.*, 2020; Štefančík & Pástor, 2023). Summarizing the data on the MAI of modal stands corresponding to the main species of forest types and ranking them revealed that the productivity scores of forest site types derived from the Ukrderzhlisproekt (n.d.) database differ substantially from the evaluation scale compiled by researchers of the Ukrainian Research Institute of Forestry and Forest Melioration (URIFFM) for native reference stands (Turkevych *et al.*, 1973) (Fig. 1).

The highest productivity scores of native reference stands were recorded in moist rich site conditions (100), fresh fairly rich site conditions (92), moist fairly rich site conditions (87), and fresh rich site conditions (82). In contrast, analysis of forest inventory materials revealed that the highest productivity scores are currently observed in modal stands of fresh fairly poor site conditions (100), fresh fairly rich site conditions (94), moist fairly poor site conditions (88), fresh poor site conditions (81), and moist fairly rich site conditions (80). A comparison of the two evaluation scales shows that consistent scores are found only in fairly rich site conditions. In poor and fairly poor site conditions, modal stands now have substantially higher productivity scores compared to the data reported for native reference stands of

Ukrainian Polissia. However, in rich site conditions, the situation is the opposite – modal stands corresponding to the main native species of forest types exhibit lower scores than native reference stands.

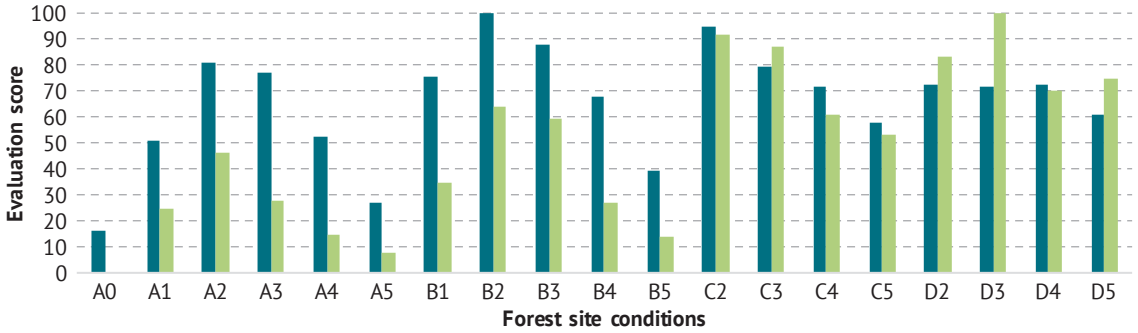

Figure 1. *Evaluation scale of productivity of native forest stands under site conditions of Ukrainian Polissia*
Source: *developed by the authors based on Ukrderzhlisproekt (n.d.) and I. Turkevych et al. (1973)*

Across different regions of Ukraine, the gap between modal and reference stands is consistently evident and is mainly driven by relative density of stocking, site index class, stand origin, and the correspondence of the main species to the forest type. For Ukraine as a whole, the actual realization of site potential averages 50-75%, indicating significant reserves. A comparison of the productivity evaluation scales of modal stands corresponding to the main native species of forest types and secondary stands, based on the analysis of the relational database of Ukrderzhlisproekt (n.d.), revealed certain differences. These were particularly pronounced in the productivity scores under rich site conditions (Fig. 2). The highest productivity scores of secondary stands were recorded in fresh rich site conditions (100), moist rich site conditions (96), fresh fairly poor site conditions (96), and fresh and moist fairly rich site conditions (88 and 86, respectively).

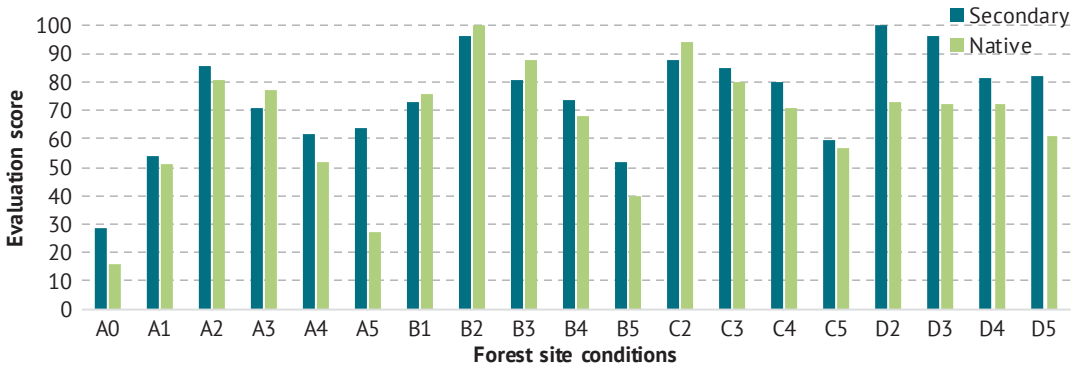

Figure 2. *Evaluation scale of productivity of modal stands corresponding to the main native species of forest types and secondary stands under site conditions of Ukrainian Polissia*
Source: *developed by the authors*

A comparison of these results with independent regional studies provides partial confirmation: native stands of target species in their "appropriate" forest types consistently achieve higher growing stock in middle- and older-age classes than secondary stands (Musienko *et al.*, 2021). This aligns with our conclusion on the differentiation of productivity scales between modal and reference stands. In spruce forests of the Ukrainian Carpathians, it has been shown that the transition from less fertile to more fertile site types sharply increases potential growing stock, with reference high-density plots exceeding modal ones several times. This further confirms that species–site correspondence and high relative density of stocking determine the upper limits of productivity, where native structures have a clear advantage (Lavnyy & Matusevych, 2022). Although secondary stands in favorable site conditions may temporarily demonstrate high productivity scores due to the rapid early growth of pioneer species, in the long term native stands are more productive in terms of growing stock and stability of increment in middle- and older-age classes, provided high density and proper silvicultural care are maintained. Accordingly, a strategy for enhancing productivity should be based on reducing the proportion of secondary stands and moving toward the structure and composition of native forest stands (Zhezhkun *et al.*, 2023).

In summary, the analysis of forest inventory data across Ukrainian Polissia revealed clear differentiation of productivity between modal, secondary, and native reference stands depending on forest-site conditions. Modal Scots pine stands demonstrated the highest mean annual increment in poor and fairly poor sites, while in rich site conditions secondary mixed stands slightly outperformed modal ones due to the presence of fast-growing species. However, native reference stands remain superior in terms of long-term stability and biomass accumulation, particularly in fertile and moist environments. These findings confirm that productivity is strongly dependent on the correspondence of dominant species to site type and that enhancing forest productivity requires gradual transformation of secondary formations toward structures and compositions characteristic of native forests.

CONCLUSIONS

The average tree species composition of modal stands differs from that of native reference stands in most forest types of Ukrainian Polissia. When the main species corresponds to the native forest type, modal stands in poor and fairly poor site conditions include a higher proportion of silver birch (*B. pendula* Roth); in fairly rich site conditions, higher proportions of silver birch and hornbeam (*C. betulus* L.); and in rich site conditions, a range of native hardwood and softwood species. In secondary stands, jack pine (*P. banksiana* Lamb.) and silver birch dominate in poor site conditions; silver birch dominates in fairly poor and fairly rich site conditions; while hornbeam (*C. betulus* L.), northern red oak (*Q. rubra* L.), Scots pine (*P. sylvestris* L.), black alder (*A. glutinosa* (L.) Gaertn.), and silver birch prevail in rich site conditions.

The mean annual increment of modal Scots pine stands in poor and fairly poor site conditions is higher than in native reference stands: by 17-58% in poor sites and by 2-48% in fairly poor sites, depending on the moisture regime. In fairly rich site conditions, the mean increment of modal stands corresponding to the main species is lower than in native reference stands by 19-37% across all site types, whereas in rich site conditions the increments of modal and native stands are similar. In the most widespread types of poor, fairly poor and fairly rich site conditions, the mean increment of modal stands corresponding to the native species exceeds that of secondary stands. By contrast, in fairly rich site conditions, secondary stands are more productive than modal stands corresponding to the native species in the most common site conditions, by 13-16%.

The productivity scores of modal stands differ considerably from the evaluation scale developed for native reference stands. Consistency was observed only in fairly rich site conditions conditions. In poor and fairly poor site conditions conditions, modal stands currently exhibit significantly higher productivity scores compared with native reference stands of Ukrainian Polissia, whereas in rich site conditions conditions the opposite trend is evident. The highest productivity scores of secondary stands were recorded in fresh and moist fairly rich site conditions, as well as in fresh fairly poor site conditions. Future research should focus on long-term monitoring of productivity dynamics under changing climatic and hydrological conditions, with particular attention to carbon balance and resilience indicators of modal and secondary stands. Expanding comparative analyses using remote sensing and process-based models would allow refinement of productivity assessment scales and support the development of adaptive, typology-based strategies for sustainable forest management in Ukrainian Polissia.

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CONFLICT OF INTEREST

None.

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Продуктивність модальних деревостанів Українського Полісся залежно від відповідності головних деревних порід типу природного лісу

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Анотація. Дослідження мало на меті оцінити склад і таксаційні характеристики наближених до природних та вторинних деревостанів, порівняти їх середній річний приріст із природними еталонними насадженнями та уточнити закономірності природної продуктивності за різних типів лісорослинних умов. Аналіз базувався на матеріалах лісовпорядкування, поєднаних із геоінформаційними ресурсами. Продуктивність оцінювалася шляхом порівняння середніх значень приросту та ранжування показників природної продуктивності. Середній видовий склад деревостанів, наближених за композицією до природних, відрізнявся від еталонних природних насаджень у більшості типів лісорослинних умов. У бідних і досить бідних умовах спостерігалася більша частка берези повислої (*Betula pendula* Roth); у досить багатих – підвищена частка берези (*B. pendula*) та грабу звичайного (*Carpinus betulus* L.); а в багатих умовах переважали комплекси аборигенних твердих і м'яколистяних порід. Вторинні деревостани характеризувалися такими закономірностями: у бідних умовах вони були переважно представлені сосною Банкса (*Pinus banksiana* Lamb.) та березою (*B. pendula*); у досить бідних і досить багатих – переважно березою (*B. pendula*); а в багатих умовах – грабом (*C. betulus*), червоним дубом (*Quercus rubra* L.), сосною звичайною (*Pinus sylvestris* L.), вільхою чорною (*Alnus glutinosa* (L.) Gaertn.) та березою (*B. pendula*). Середній приріст модальних насаджень сосни звичайної перевищував еталонні природні показники на 17-58 % у бідних лісорослинних умовах і на 2-48 % у досить бідних, залежно від режиму зволоження ґрунту. У досить багатих умовах приріст насаджень, наближених за складом до природних, був нижчим на 19-37 %, тоді як у багатих умовах показники приросту були подібними. У найпоширеніших типах лісорослинних умов – бідних, досить бідних і досить багатих – модальні природні деревостани виявилися продуктивнішими за вторинні, тоді як у багатих умовах вторинні насадження переважали на 13-16 %. Показники природної продуктивності модальних насаджень суттєво відрізнялися від еталонних шкал: вони були вищими у бідних і досить бідних умовах, але нижчими – у багатих. Найвищі значення природної продуктивності вторинних деревостанів спостерігалися у свіжих і вологих багатих лісорослинних умовах, а також у свіжих досить бідних умовах. Отримані результати стали науковою основою для уточнення шкал природної продуктивності та типологічно обґрунтованого планування лісогосподарських заходів

Ключові слова: лісорослинні умови; середній річний приріст; видовий склад деревостанів; вторинний деревостан; еталонні природні насадження; шкала оцінювання продуктивності