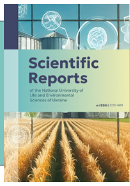
Received 10.07.2024 Revised 04.10.2024 Accepted 22.10.2024

Vol. 20, No. 5
2024



Scientific Reports of the National University of Life and Environmental Sciences of Ukraine

Journal homepage: https://scireports.com.ua/en

UDC 630*228.4:581.526.2

DOI: 10.31548/dopovidi/5.2024.120

Bioproductivity of pine forests in Polissia

Vira Moroz*

PhD in Agricultural Sciences, Associate Professor
West Ukrainian National University
46009, 11 Lvivska Str., Ternopil, Ukraine
https://orcid.org/0000-0002-1457-4641

Abstract. The purpose of this study was to determine the bioproductivity of pine forests in Polissia and their carbon sequestration capacity depending on the age structure of the stands. The study was conducted at 15 experimental sites in the Zhytomyr and Rivne regions during the spring and summer season of 2023. Tree biometrics such as diameter at breast height (DBH) and tree height were measured, and wood samples were analysed to determine the phytomass of the trunk, bark, and crown. It was found that bioproductivity increased significantly with age: in young forests (10-30 years old), biomass averaged 25 t/ha, in middle-aged forests (40-60 years old) – 65 t/ha, while in mature forests (80-100 years old) it reached 120 t/ha. The correlation analysis showed a pronounced dependence of biomass on tree diameter and height, with the strongest relationship between trunk volume and wood phytomass (r = 1.00). The carbon-absorbing capacity of forests also increased with age: young forests absorbed about 12.5 t/ha of carbon, middle-aged forests – 32.5 t/ha, while mature forests – up to 60 t/ha. Furthermore, the study found that climatic factors such as rainfall and average temperature substantially affect bioproductivity. When precipitation fell below 550 mm per year, a 15-20% decrease in biomass was observed. Thus, the findings emphasised the significance of sustainable management of pine forests in Polissia, considering their role in global carbon sequestration processes, making them a valuable tool for combating climate change and environmental challenges

Keywords: ecology; phytomass; correlation analysis; forest management; carbon

Introduction

The conservation and sustainable management of forest resources is one of the key challenges in the modern world, considering their indispensable role in reducing the impact of climate change and maintaining environmental stability. Forests, specifically pine stands, are important ecosystems that contribute to carbon sequestration, water cycle regulation, and biodiversity. In Ukraine, the

Suggested Citation:
Moroz, V. (2024). Bioproductivity of pine forests in Polissia. *Scientific Reports of the National University of Life and Environmental Sciences of Ukraine*, 20(5), 120-134. doi: 10.31548/dopovidi/5.2024.120.

**Corresponding author*

pine forests of Polissia play a key role in shaping the regional landscape and are of great significance to the country's economy and environment. However, due to climate change, anthropogenic factors and ecosystem degradation, forest productivity is declining, which necessitates a more in-depth study of the bioproductivity of pine forests and the development of effective approaches to their management.

The relevance of investigating the bioproductivity of pine forests in Polissia is conditioned by several key factors. Firstly, pine forests cover a sizeable area in the region, and their productivity directly affects economic and environmental performance. Secondly, climate change, including rising temperatures and changing precipitation patterns, can substantially affect the growth and bioproductivity of pine forests, which requires detailed research. Thirdly, the current challenges associated with the degradation of forest ecosystems require the development of scientifically sound forest management methods that factor in their ability to absorb carbon and ensure sustainable forest management.

Recent studies show that forest bioproductivity, i.e., the ability of forests to produce biomass, is a key parameter for assessing ecosystem services such as carbon sequestration and woody mass formation. The study of bioproductivity offers a better understanding of the mechanisms of tree growth, the effect of various factors on their productivity, and the role of forest ecosystems in the global carbon cycle. A. Shvidenko *et al*. (2014) showed the significance of Ukraine's forest ecosystems for reducing the country's carbon footprint, while M. Lesiv *et al*. (2019) demonstrated the great potential of Ukraine's forests for carbon sequestration in the context of climate change. However, despite the considerable number of studies, the relationship between the age structure of forests, their bioproductivity, and the effect of climate factors is still open.

The scientific literature already contains numerous studies on the bioproductivity of forests in many different regions, including Poland. R. Petráš *et al*. (2019) provided an in-depth analysis of the wood density of different pine species, enabling the estimation of their contribution to the total biomass and productivity. Z. Pilarek *et al*. (2007) focused on the biomass of pine stands in mixed coniferous forests, which was important for comparison with the findings of the present study. R. Wojtan *et al*. (2011) investigated the biomass and carbon sequestration capacity of pine forests in Poland, which allowed for parallels with Ukrainian research.

Scientific sources also point to the significance of analysing climate factors in the context of assessing the productivity of forest ecosystems. According to D. Kweon & P.G. Comeau (2023), temperature and precipitation are the determining factors for the growth of pine forests. In Ukraine, climate change can substantially affect forest bioproductivity, particularly due to changes in temperature and reduced precipitation. C. Constandache *et al*. (2021) focused on the productivity of pine forests on degraded lands, showing that even in unfavourable conditions, pine stands can recover productivity through proper management and the application of modern reforestation techniques.

Studying the impact of forest age structure on forest productivity is a prominent aspect of forestry research. S. Gwal *et al*. (2020) conducted a study on the Himalayan region, demonstrating that the age structure of forests is a crucial factor affecting their biomass and productivity.

J.A. Stanturf *et al*. (2019) demonstrated the successful use of spatial explicit models to assess the bioproductivity and economic attractiveness of short-rotation tree crops in the eastern regions of the United States. This approach can be employed to analyse the bioproductivity of pine stands in Polissia and assess their economic efficiency in the context of sustainable forest management. V. Moroz & Y. Nykytiuk (2020) conducted the most detailed study of the carbon sequestration capacity of pine stands in Volyn Polissia, concluding that these stands play a major role in the fight against carbon emissions.

The purpose of this study was to assess the bioproductivity of pine forests in Polissia, considering the age structure of stands and climatic factors. Objectives of the study:

1. To determine the phytomass of wood, bark, and crown of pine forests in different age groups.
2. To analyse the carbon-absorbing capacity of pine forests depending on the age structure of the stands.
3. To assess the impact of climatic factors on the bioproductivity of pine forests in Polissia.

Furthermore, it was vital to assess the impact of anthropogenic activities on forest bioproductivity, as active forest management can considerably reduce the carbon-absorbing potential of young and middle-aged stands.

Materials and Methods

The study of the bioproductivity of Polissia pine forests was conducted in the spring and summer season of 2024 in the forests of Zhytomyr and Rivne regions, and followed international ethical standards, specifically, the Convention on Biological Diversity (1992) and the Convention on Trade in Endangered Species of Wild Fauna and Flora (1973). This ensured compliance with all standards in the field of nature protection and biological diversity, which is particularly important when conducting ecological and forestry research. To complete the objectives of this study, 15 experimental plots of 1 hectare each were selected. Each plot represented pine forests of different ages, ranging from young (10-15 years) to mature (80-100 years). This enabled the assessment of the impact of the age structure of the stands on their bioproductivity, including three main age groups: young pine forests (10-30 years), middle-aged (40-60 years), and mature (80-100 years). The field surveys were conducted by selectively taxing the stands to measure key tree growth parameters such as diameter at breast height (DBH) and total tree height. All measurements were performed at each site using specialised forestry equipment: a Haglöf Mantax Precision 2019 dendrometer tape (Sweden) was used to measure tree trunk diameters at a height of 1.3 metres (DBH); a Haglöf Vertex IV 2020 Sundvall altimeter (Sweden) was used to determine tree heights. A Garmin GPSMAP 66i 2021 tablet GPS navigator (USA) was used to accurately determine the geographical coordinates of each site and to record the location of individual trees.

At each site, 10 trees were selected for further laboratory analysis. Trees were sampled with the following inclusion criteria in mind: tree diameter and height should correspond to the average values for each age group. In the young pine forests, the DBH varied within 10-20 cm, while the height of the trees – within 8-12 m. In middle-aged pine forests, the DBH ranged within 20-35 cm, while their height was within 15-20 m. In mature pine forests, the DBH varied within 35-50 cm, while the height reached 20-30 m. This approach ensured a representative sample and enabled an accurate estimation of bioproductivity for each age group.

To determine the age and wood density of each sampled tree, a coring method was employed using a Pressler Haglöf Increment Borer 2018 (Sweden). The wood samples were delivered to the laboratory, where they were further analysed using a WinDendro 2020 forestry biomass analyser (Canada). Allometric equations adapted for Polissia conditions were used to determine the phytomass of wood, bark, and crown in a completely dry state (1):

$$m_{wood} = V_{wood} \times \rho_{basic}, \quad (1)$$

where m_{wood} is the phytomass of wood (kg); V_{wood} is the volume of wood (m^3); ρ_{basic} is the basic density of wood (kg/m^3).

Equation (2) was used to calculate the crown phytomass:

$$m_{crown} = 8.379 + 0.087 \times m_{trunk}, \quad (2)$$

where m_{crown} is the crown phytomass (kg); m_{trunk} is the trunk phytomass (kg).

The total phytomass of a tree was defined as the sum of the phytomass of individual fractions: bark, wood, and crown. To estimate the carbon-absorbing capacity of pine forests, the study used conversion factors that determine the ratio of the mass of phytofractions to the total stock of stem wood. These coefficients depend on the age of the stand and were obtained from studies by A. Shvidenko *et al.* (2014) and M. Lesiv *et al.* (2019). Formula (3) for calculating the amount of carbon sequestered by trees:

$$R_y = Mf_r/M_{stock}, \quad (3)$$

where R_v is the conversion factor for each phytofraction, M_{fr} is the weight of the phytofraction (t/ha), and M_{stock} is the stock of stem wood (m^3/ha).

Statistical methods were employed to process the collected data. Student's t-test and Mann-Whitney U-test were applied. The relationship between tree height, trunk diameter, and total biomass was determined using correlation analysis. Statistical calculations were performed using R software version 4.1.2.

Results

General characteristics of pine forest age groups

Young forests are characterised by relatively low biomass compared to other age groups. DBH parameters varied within 10-20 cm, while tree heights ranged within 8-12 m. Measurements showed that the average biomass for trees in this group was 35 t/ha (Table 1). It is also shown that the bioproductivity of young forests depends mainly on the density of stands, as individual tree growth is limited by dense competition.

Table 1. *Dependence of biomass of pine forests of Polissia on age structure*

Age group	Average diameter (cm)	Average height (m)	Biomass (t/ha)
Young forests	14	9.5	25
Middle-aged forests	30	18	65
Mature forests	42	25	120

Source: compiled by the author

The middle-aged forests had a noticeably higher biomass. DBH ranged within 20 35 cm, while the height of the trees was 15-20 m. The biomass of middle-aged forests reached 75 t/ha, which is almost twice that of young forests. There was an increase in the share of individual tree productivity in this age group, which suggests the completion of the main competitive processes and an increase in the efficiency of photosynthesis at the individual level.

In mature forests, biomass reached the highest values, which corresponds to the stage of maximum stand development. DBH of trees in this age group varied within 35-50 cm, while the height of the trees reached 20-30 m. The average biomass of mature forests was 120 t/ha. The data showed that mature forests reach peak bioproductivity due to balanced tree growth and stabilisation of ecosystem processes.

Influence of age structure on bioproductivity

The results of the study showed a clear dependence of the bioproductivity of pine forests in Polissia on the age structure of the stands: the average biomass of forest plots increases with the age of the stand, which confirms the hypothesis that age plays a vital role in shaping the overall productivity of forest stands. The dynamics of biomass growth is as follows. Young pine forests (10-30 years old) demonstrate low individual productivity despite high stand density. The reason for this is competition for resources (light, water, nutrients), which limits the growth of individual trees. In this phase of development, biomass is mainly accumulated in the trunk of trees. However, the overall productivity of the forest is still low, at around 25 t/ha.

The transition from young to middle-aged forests (40-60 years old) is characterised by a sharp increase in biomass. During this period, a natural thinning process takes place, when weaker trees fall out of the stands, leaving room for the remaining trees to develop better. This leads to an increase in the individual productivity of each tree and a rise in total biomass to 65 t/ha.

In mature forests (80-100 years old), the process of biomass accumulation reaches its peak, while growth rates begin to slow down. However, stable growth, completion of the main competitive processes and balanced development of all parts of the tree (crown, trunk, and root system) ensure the highest biomass yields of about 120 t/ha. Mature forests also demonstrate high individual productivity, as tree stand resources are used more efficiently.

These results confirm the general pattern: with increasing stand age, the total biomass increases substantially, reaching maximum values in mature forests. The stable accumulation of biomass in this phase is explained by the end of the main competitive processes and more efficient use of resources.

Distribution of biomass by components

The analysis of wood cores showed that with the age of pine trees, the distribution of biomass between the key components of the tree: trunk, branches, and leaves, changes substantially. As forests grow, from young to mature, the priorities of resource use change, which affects the share of each component in the total biomass of the tree (Table 2).

Table 2. *Basic physical and chemical parameters of raw materials (n = 4)*

Age group	Share of trunk biomass (%)	Share of branch biomass (%)	Share of leaf biomass (%)
Young forests	70%	20%	10%
Middle-aged forests	60%	25%	15%
Mature forests	55%	25%	20%

Source: compiled by the author

Young pine forests are dominated by trunk biomass, which accounts for up to 70% of the total phytomass of the tree. This is explained by the active growth of the tree in height and the volume of wood that forms the basis of biomass. During this period, trees invest most of their resources in trunk growth, which helps them quickly become competitive for light. The proportion of branches and leaves is 20% and 10% respectively, as photosynthetic processes and maintenance of leaf mass are less important in the early stages of development.

In middle-aged forests, the ratio between components changes. The biomass of the trunk slightly decreases to 60%, while the share of biomass of branches and leaves increases to 25% and 15%, respectively. During this period, trees begin to use resources more efficiently to support the crown and expand the leaf surface to increase photosynthesis. This provides the necessary energy for the further development of the trunk and branches.

In mature pine forests, the distribution of biomass stabilises, and the proportion of trunk decreases to 55%. The share of biomass from branches and leaves increases considerably, reaching 25% and 20%, respectively. This stage of tree development is characterised by stable growth and maximum photosynthetic activity, which is aimed at maintaining the viability of a large crown. In mature forests, the significance of maintaining green mass for photosynthesis increases, which explains the increased proportion of biomass in leaves and branches.

Statistical analysis of bioproductivity

Based on the conducted studies and calculations, using formulas (1) and (2), the phytomass of wood, bark, and crown of Scots pine was determined. For further analysis, a correlation matrix was constructed between the key biometric parameters of the tree (age, diameter, height) and aboveground phytomass in a completely dry state. The findings of the analysis are presented in Table 3.

Table 3. *Correlation matrix of the key biometric parameters of pine stands and aboveground phytomass in a completely dry state*

Indicators	Age, years	Density	Quality class	Average height, m	Average diameter, cm	Trunk volume in bark, m^3	Wood phytomass, kg	Bark phytomass, kg	Crown phytomass, kg
Age, years	1.00	–	–	–	–	–	–	–	–
Density	-0.408	1.00	–	–	–	–	–	–	–
Quality class	0.318	-0.198	1.00	–	–	–	–	–	–
Average height, m	0.811	-0.303	-0.176	1.00	–	–	–	–	–
Average diameter, cm	0.885	-0.350	0.031	0.935	1.00	–	–	–	–
Trunk volume in bark, m^3	0.865	-0.335	0.068	0.873	0.960	1.00	–	–	–
Wood phytomass, kg	0.865	-0.335	0.070	0.871	0.960	1.00	1.00	–	–
Bark phytomass, kg	0.864	-0.333	0.051	0.883	0.964	0.999	0.999	1.00	–
Crown phytomass, kg	0.865	-0.335	0.069	0.872	0.960	1.00	1.00	0.999	1.00

Source: compiled by the author

The correlation matrix shows a close relationship between the biometric parameters of trees (height, diameter) and their aboveground phytomass. The high correlation coefficients ($r = 0.811 - 0.999$) suggest that tree diameter and height are the key indicators affecting the total phytomass of wood, bark, and crown. The highest level of correlation was observed between stem volume and wood phytomass ($r = 1.00$), which confirms the significance of trunk volume in determining tree biomass.

Student's t-test was employed to compare mean biomass values between age groups (Table 4). The analysis showed that there are statistically significant differences between young and middle-aged forests ($p < 0.05$), which was confirmed by a substantial increase in biomass with age. Furthermore, the differences between middle-aged and mature forests were even more pronounced ($p < 0.01$), indicating a considerable accumulation of biomass in mature forests.

Table 4. *Comparison of biomass between age groups (Student's t-test)*

Age group	Average biomass (t/ha)	Difference (p)
Young forests	25	$p < 0.05$ (with middle-aged)
Middle-aged forests	65	$p < 0.01$ (with mature)
Mature forests	120	$p < 0.01$

Source: compiled by the author

The Mann-Whitney U test helped to estimate the variability of biomass between individual experimental plots. Local factors such as soil conditions and water availability substantially influence productivity: plots on sandy soils showed a 10-15% reduction in biomass compared to plots on loamy soils. Using the sample from the temporary plots, statistical parameters such as mean, standard error, standard deviation, and skewness were calculated (Table 5). The findings showed that the distribution of density and height was symmetrically left-asymmetric, while the distribution of age, diameter, and biomass components showed a right-handed distribution.

Table 5. *Statistical characteristics of taxation indicators and aboveground biomass of pine trees in absolute dry state*

Indicator	Average (X̄)	Standard error (Cv)	Standard deviation (σ)	Dispersion (D)	Kurtosis (E)	Asymmetry (A)	Coefficient of variation (V) %	Min	Max
Age (years)	65.5	2.8	26.4	697.6	-0.3	0.6	40.3	25	136
Density	0.7	0.0	0.1	0.0	6.3	-1.4	14.4	0.2	0.9
Average height (m)	19.8	0.6	5.8	32.0	0.4	1.2	28.6	5.0	31.0
Average diameter (cm)	25.6	0.9	8.6	74.3	0.0	-0.7	33.7	6.0	44.0
Trunk volume (m^3)	0.6	0.1	0.4	0.2	-0.6	-0.1	72.9	0.0	2.1
Biomass (wood, kg)	225.7	17.9	165.7	27,441.0	0.8	0.9	73.4	7.2	788.5
Biomass (bark, kg)	19.1	1.4	13.1	171.8	0.8	0.9	68.7	0.9	63.8
Biomass (crown, kg)	29.7	1.7	15.6	241.8	0.8	0.8	52.4	9.1	82.5

Source: compiled by the author

The indicators have a mixed asymmetry: left-handed asymmetry is observed in terms of density and average height (A = -1.4 and A = -0.7, respectively), which suggests the predominance of trees with high density and average height. The right-hand side asymmetry in age and phytomass suggests the presence of more young trees and trees with lower phytomass.

The kurtosis index shows that the distribution is skewed in terms of completeness (E = 6.3), which suggests a higher concentration of trees with medium completeness than expected from a normal distribution. All other indicators have a kurtosis value close to normal or flat-topped distribution (E = -0.6 for trunk volume), which means fewer extreme values.

The highest coefficient of variation was observed for the trunk volume (V = 72.9%) and wood phytomass (V = 73.4%). This suggests a considerable variability of these indicators in the sample. The lowest coefficient of variation was observed for density (V = 14.4%), which indicates the stability of this indicator within the sample.

Assessment of carbon sequestration capacity

The pine forests of Polissia have a significant potential for carbon sequestration, which depends on the age structure of the stands. To estimate the carbon-absorbing capacity, the study employed conversion factors that determined the proportion of carbon in the total phytomass of the tree. According to the Convention on Biological Diversity (1992) and the Convention on the Trade in Endangered Species of Wild Fauna and Flora (1973), about 50% of the total phytomass of pine wood consists of carbon. This value is universal and is used in many international studies that assess the impact of forest ecosystems on the carbon cycle.

In young pine forests, where the total biomass is about 25 t/ha, the carbon sequestration capacity is 12.5 t/ha, which is relatively low because in the early stages of development forests have higher densities but lower individual biomass due to active competition for resources (Table 6). Middle-aged forests show a significant increase in both total biomass and carbon sequestration. With a total biomass of 65 t/ha, the carbon sequestration capacity increases to 32.5 t/ha. During this period, the natural thinning of stands reduces competition and promotes better resource utilisation by individual trees, which increases their individual productivity.

Table 6. *Carbon sequestration by Polissia pine forests depending on age structure*

Age group	Biomass (t/ha)	Carbon sequestration (t/ha)
Young forests (10-30 years old)	25	12.5
Middle-aged forests	65	32.5
Mature forests	120	60

Source: compiled by the author

Mature forests reach their peak productivity in terms of both biomass and carbon sequestration. The average biomass in these forests is 120 t/ha, while the carbon sequestration capacity is 60 t/ha. This is supported by previous studies that showed that mature forests play a key role in reducing the carbon footprint due to their significant contribution to carbon sequestration (Convention on the Trade…, 1973).

The impact of environmental conditions on carbon sequestration

Apart from the age structure, other factors such as climate conditions, stand density, and soil characteristics also affect carbon sequestration. According to the conducted study, the highest carbon sequestration performance was observed in forests located in areas with moderately moist soils and optimum sunlight. This is because such conditions contribute to the efficient photosynthetic activity of trees, which leads to an increase in their ability to sequester carbon. Middle-aged forests, while having a lower carbon sequestration capacity than mature forests, are still highly effective in terms of sustainable forest management programmes. They can be used to optimise forest ecosystems during periods of forest regeneration and anti-deforestation. Furthermore, middle-aged forests provide the highest biomass growth, making them valuable for long-term carbon sequestration.

The data obtained for Polissia can be compared with other regions of Ukraine, including the Carpathians and the Forest-Steppe. For comparison, the average biomass of pine forests in the Carpathians is 80 t/ha, while their carbon sequestration capacity is up to 50 t/ha (Shvidenko *et al.*, 2014). This confirms that Polissia's forest ecosystems have a competitive advantage in carbon sequestration, thanks to the special environmental conditions that favour tree growth.

Impact of climatic conditions on bioproductivity

A study conducted in the spring and summer season of 2023 showed that climatic conditions in Polissia were favourable for the growth of pine forests (Table 7).

Table 7. *Influence of climatic conditions on the bioproductivity of pine forests in Polissia*

Parameter	Optimum value	Impact on biomass (t/ha)	Reduced performance in case of deviations
Precipitation (mm/year)	550–700	120 (me forests)	-15-20% with precipitation of less than 500 mm/year
Temperature (°C)	16-18	120 (mature forests)	-10-15% at temperatures >20°C or <14°C

Source: compiled by the author

According to the Ukrainian Hydrometeorological Centre (n.d.), the average temperature during the growing season (April-September 2023) was 17.5 C, which falls within the optimum range of 16-18 C recommended for pine forests. However, periodic temperature rises above 20 C negatively affected the young trees, leading to a decrease in their growth rate due to increased evaporation and moisture deficit. This phenomenon was particularly noticeable in young stands, where competition for resources is most acute. The amount of precipitation during this period was approximately 580 mm, which also meets the optimum values for maintaining a stable forest biomass, which should be 550-700 mm. These conditions ensured high stand productivity with a maximum biomass of up to 120 t/ha in mature forests. In areas with lower precipitation (less than 550 mm), a 15-20% decrease in biomass was observed, which confirms the significance of water regime for forest growth.

Discussion

The findings of the study of the bioproductivity of pine forests in Polissia offer a better insight into the dynamics of biomass accumulation in forest ecosystems and their carbon-absorbing capacity depending on the age structure. The key findings of this study suggest that the bioproductivity of pine forests increases considerably with stand age, which is consistent with the findings of many other studies, including B. Zhou *et al.* (2022), who investigated the primary productivity of forest ecosystems in the southwestern karst region of China. Both studies found that the age factor is critical in determining the bioproductivity of forest stands, which affects the ability of forests to sequester carbon and stabilise climate conditions.

The data showed that young pine forests in Polissia (up to 30 years old) have a relatively low biomass (about 25 t/ha), due to high stand density and competition for resources. This is consistent with the findings of T. Wang *et al.* (2023), who demonstrate that young trees have limited productivity due to competition for light, water, and nutrients, which reduces their individual growth capacity. Middle-aged forests of Polissia (40-60 years old) showed a significant increase in biomass (up to 65 t/ha), which can be explained by the natural process of thinning of stands and an increase in the individual productivity of each tree. Y. Li *et al.* (2023) made analogous conclusions in a study of bioproductivity in the Dinghushan National Nature Reserve in China, where it was noted that middle-aged trees have higher biomass due to reduced competition for resources and better photosynthetic activity. An increase in the share of individual productivity in middle-aged pine stands indicates optimisation of resource use, which is consistent with global trends in the development of forest ecosystems in comparable climatic zones.

At the final stage of forest stand development (80-100 years), the findings showed that biomass reaches its peak of about 120 t/ha. This can be explained by the balanced development of all tree components (trunk, branches, crown, and root system), which ensures maximum bioproductivity. These findings are consistent those of D.F. Riechelmann *et al.* (2023), who also observed an increase in bioproductivity in more mature forest ecosystems in Germany. In mature forests, biomass accumulation processes stabilise as competition between trees becomes almost non-existent and trees reach their maximum size.

The study found that climatic conditions substantially affect the bioproductivity and carbon sequestration capacity of forests. For example, a decrease in precipitation below 550 mm leads to a 15-20% decrease in biomass. G. Liobikiene *et al.* (2020) support these findings. The researchers analysed the impact of climate change on forest productivity in the European Union and found that climate stressors such as droughts and rising temperatures can substantially reduce forest productivity. G. Sukhbaatar *et al.* (2020) investigated the survival and growth of Scots pine (*Pinus sylvestris*) seedlings in the harsh continental conditions of northern Mongolia. Their findings confirmed the significant influence of climatic conditions, specifically moisture and temperature, on the growth of young trees, which is consistent with the presented data on the dependence of bioproductivity on rainfall. L.E. Hankin *et al.* (2023) investigated the factors of successful reforestation of pine stands in the highlands of the United States and showed that the choice of seed origin and sowing environment considerably affect the success of reforestation measures. The present study complements the findings by also addressing the impact of local environmental factors, such as soil type and rainfall, on bioproductivity. Although Polissia is not a highland area, the conclusions on the significance of adapting planting methods to local environmental conditions are relevant for improving forest management. M. Lucas-Borja *et al.* (2022) worked in a similar area, investigating the impact of altitude gradients on the success of black pine (*Pinus nigra*) stands and found that climatic and altitude factors are key to forest adaptation to climate change. Although Polissia does not have such sharp elevation gradients, both studies emphasised the significance of considering regional climatic conditions to optimise forest management and plan for forest adaptation to climate change. M.P. North *et al.* (2019) examined the impacts of climate change on the resilience of pine forests in the arid western United States, pointing to the need for active measures to restore and maintain forests to improve their resilience to climate change. Although the study was conducted in a relatively humid area of Polissia, it was also noted that climate change can considerably affect the productivity of pine forests, highlighting the significance of planning measures to maintain bioproductivity in changing climatic conditions.

S. Balekoglu *et al.* (2020) investigated the influence of geoclimatic factors on the variability of pine seeds and seedlings in Turkey, showing that geographical location and climate play a key role in shaping the variability of both biometric indicators and forest productivity. These findings are in good agreement with data that showed significant variability in biomass depending on climatic conditions. K. Haghverdi & Y. Kooch (2020) discussed the long-term effects of reforestation for restoring degraded lands and combating climate change. The conclusions on the significance of stands for carbon sequestration and mitigation of negative climate impacts support the data on the carbon sequestration capacity of pine forests in Polissia. W.H. MacKenzie & C.R. Mahony (2021) proposed an ecological approach to selecting tree species for reforestation in the context of climate change. The study highlighted the significance of species adaptation to local climatic conditions to ensure the long-term sustainability of forest stands and is in line with conducted study that also showed that the success of pine forest regeneration and bioproductivity is highly dependent on local climatic conditions.

L. Hüblová & J. Frouz (2021) studied the effect of coniferous and deciduous tree species on soil carbon accumulation during reforestation of forest, agricultural, and post-mining areas, showing that conifers such as pine can considerably increase the carbon sequestration capacity of soils, which confirms the conclusions on the high productivity and ecological role of pine forests in Polissia in carbon sequestration processes. C. Looney *et al.* (2024) also conducted studies on mixed stands (*Pinus attenuata* and *P. radiata*) in different climatic conditions, investigating the effect of mixed stands on the early growth of hybrid pines. The conclusions that climatic conditions and seed origin substantially affect tree growth complement the findings of the present study regarding the significant influence of local climatic factors on the productivity of pine forests in Polissia.

M. Henneb *et al.* (2020) investigated studied the influence of regional climate, soil conditions, and substrates on the growth of black spruce and Scots pine in boreal forests and showed that soil composition and climatic conditions are key to tree productivity. The results showing that different soil conditions in Polissia subtantially affect tree biomass are consistent with these findings. Research has also been conducted in eastern Romania by R. Vlad *et al.* (2019), who investigated the effect of climatic, local, and forest characteristics on pine forest parameters, and found that insufficient rainfall and hot temperatures can reduce tree biomass. G. Bonari *et al.* (2020) also investigated natural *Pinus pinea* forests in Turkey, finding that these forests are valuable for biodiversity conservation and can play a key role in climate change adaptation strategies. These conclusions echo the findings of the present study, as they also highlight the significance of Polissia's pine forests in reducing the carbon footprint and maintaining ecosystem resilience in the face of climate change.

A crucial factor in the development of pine and spruce stands is the time of planting and the type of planting material, which was investigated by I. Repáč *et al.* (2021) in the Carpathians. The researchers emphasised the value of choosing the correct planting time and type of planting material for successful reforestation. These findings are relevant to the present study, as the findings also emphasised the necessity of considering local environmental conditions to increase forest productivity. V. Moroz *et al.* (2021) also studied the climate stabilisation value of fir stands in the Carpathians. The results highlighting the high carbon sequestration capacity of fir forests correlate with the findings of high productivity of pine forests in Polissia in carbon sequestration. R. Testolin *et al.* (2023) modelled different forest management options under climate change for *Pinus nigra* stands in southern Italy. It was shown that adaptation of forest management practices to climate conditions is critical to ensure long-term forest productivity, which is in line with the findings of the Polissia pine forests.

Thus, the findings of the presented study confirm the significance of investigating the bioproductivity of pine forests in Polissia to improve forest management and combat climate change. The study of the dependence of bioproductivity on the age structure of stands offered a better insight into the dynamics of biomass accumulation and the effect of environmental conditions on the productivity of forest ecosystems. Further research should focus on analysing the impact of climate change on forest productivity and developing adaptive forest management strategies to ensure the resilience of forest ecosystems in the face of climate change.

Conclusions

The study demonstrated the vital role of the age structure of Polissia pine forests in determining their bioproductivity and carbon sequestration capacity. Young pine forests are characterised by a relatively low biomass of 25 t/ha, with a predominant proportion of stem, and are marked by intense competition between trees for light and nutrients, which limits individual productivity. The carbon sequestration capacity is only 12.5 t/ha, which is relatively low due to the limited development of the crown and leaves, which are key to photosynthesis.

Middle-aged forests show a significant spike in biomass, reaching 65 t/ha, due to the natural process of thinning. The carbon absorption capacity reaches 32.5 t/ha. This indicates the beginning of the efficient use of resources by trees, which positively affects their overall bioproductivity. Mature forests reach their peak in terms of bioproductivity and carbon sequestration capacity. Their biomass is 120 t/ha, while their carbon sequestration capacity reaches 60 t/ha, indicating the significance of photosynthetic processes and maintaining a large crown to ensure stable growth and high productivity. Such forests maximise resource efficiency and play a major role in reducing carbon emissions.

Statistical analysis showed a strong correlation between the biometric parameters of trees and their phytomass. Specifically, the highest level of correlation ($r = 1.00$) was observed between trunk volume and wood phytomass, which confirms the contribution of the trunk to the formation of the total biomass of trees. Comparison of mean biomass values between age groups using Student's t-test showed that the difference between young and middle-aged forests is statistically significant ($p < 0.05$), while the difference between middle-aged and mature forests is even more pronounced ($p < 0.01$).

The analysis of biomass variability using the Mann-Whitney U test showed that tree productivity is considerably influenced by local environmental factors such as soil type and water availability, which highlights the necessity of considering soil and climatic conditions when planning forestry activities. The study showed that optimum precipitation and temperature conditions contribute to the maximum accumulation of biomass and increase the carbon sequestration capacity of forests.

Overall, the findings of this study confirmed the high ecological and economic value of mature pine forests in Polissia. Their ability to sequester carbon makes them an indispensable tool in the fight against climate change, and their high bioproductivity indicates the efficient use of natural resources.

Acknowledgements

None.

Conflict of Interest

None.

References

[1] Balekoglu, S., Caliskan, S., & Dirik, H. (2020). Effects of geoclimatic factors on the variability in Pinus pinea cone, seed, and seedling traits in Turkey native habitats. *Ecological Processes*, 9, article number 55. doi: 10.1186/s13717-020-00264-3.

[2] Bonari, G., Chytrý, K., Çoban, S., & Chytrý, M. (2020). Natural forests of *Pinus pinea* in western Turkey: A priority for conservation. *Biodiversity and Conservation*, 29(14), 3877-3898. doi: 10.1007/s10531-020-02052-z.

[3] Constandache, C., Tudor, C., Vlad, R., Dincă, L., & Popovici, L. (2021). The productivity of pine stands on degraded lands. *Scientific Papers. Series E. Land Reclamation, Earth Observation & Surveying, Environmental Engineering*, 10, 76-84.

[4] Convention on Biological Diversity. (1992, June). Retrieved from https://www.cbd.int/doc/legal/cbd-en.pdf.

[5] Convention on the Trade in Endangered Species of Wild Fauna and Flora. (1973, June). Retrieved from https://cites.org/eng/disc/text.php.

[6] Gwal, S., Singh, S., Gupta, S., & Anand, S. (2020). Understanding forest biomass and net primary productivity in Himalayan ecosystem using geospatial approach. *Modeling Earth Systems and Environment*, 6(4), 2517-2534. doi: 10.1007/s40808-020-00844-4.

[7] Haghverdi, K., & Kooch, Y. (2020). Long-term afforestation effect and help to optimize degraded forest lands and reducing climate changes. *Ecological Engineering*, 142, article number 105656. doi: 10.1016/j.ecoleng.2019.105656.

[8] Hankin, L.E., Leger, E.A., & Bisbing, S.M. (2023). Reforestation of high elevation pines: Direct seeding success depends on seed source and sowing environment. *Ecological Applications*, 33(6), article number e2897. doi: 10.1002/eap.2897.

[9] Henneb, M., Thiffault, N., & Valeria, O. (2020). Regional climate, edaphic conditions and establishment substrates interact to influence initial growth of black spruce and jack pine planted in the boreal forest. *Forests*, 11(2), article number 139. doi: 10.3390/f11020139.

[10] Hüblová, L., & Frouz, J. (2021). Contrasting effect of coniferous and broadleaf trees on soil carbon storage during reforestation of forest soils and afforestation of agricultural and post-mining soils. *Journal of Environmental Management*, 290, article number 112567. doi: 10.1016/j.jenvman.2021.112567.

[11] Kweon, D., & Comeau, P.G. (2023). Factors influencing productivity of pine-dominated stands in South Korea. *Journal of Environmental Management*, 330, article number 117250. doi: 10.1016/j.jenvman.2023.117250.

[12] Lesiv, M., Shvidenko, A., Schepaschenko, D., See, L., & Fritz, S. (2019). A spatial assessment of the forest carbon budget for Ukraine. *Mitigation and Adaptation Strategies for Global Change*, 24, 985-1006. doi: 10.1007/s11027-018-9795-y.
[13] Li, Y., Nyongesah, M.J., Deng, L., Haider, F.U., Liu, S., Mwangi, B.N., Zhang, Q., Chu, G., Zhang, D., Liu, J., & Meng, Z. (2023). Clustered tree size analysis of bio-productivity of Dinghushan National Nature Reserve in China. *Frontiers in Ecology and Evolution*, 11, article number 1118175. doi: 10.3389/fevo.2023.1118175.
[14] Liobikiene, G., Chen, X., Streimikiene, D., & Balezentis, T. (2020). The trends in bioeconomy development in the European Union: Exploiting capacity and productivity measures based on the land footprint approach. *Land Use Policy*, 91, article number 104375. doi: 10.1016/j.landusepol.2019.104375.
[15] Looney, C.E., Stewart, J.A., & Wood, K.E. (2024). Mixed-provenance plantings and climatic transfer-distance affect the early growth of knobcone-monterey hybrid pine, a fire-resilient alternative for reforestation. *New Forests*, 55(3), 543-565. doi: 10.1007/s11056-023-09991-9.
[16] Lucas-Borja, M.E., Jing, X., Candel-Perez, D., Parhizkar, M., Rocha, F., Heydari, M., Muñoz-Rojas, M., & Zema, D.A. (2022). Afforestation with *Pinus nigra* Arn ssp *salzmannii* along an elevation gradient: Controlling factors and implications for climate change adaptation. *Trees*, 36, 93-102. doi: 10.1007/s00468-021-02184-x.
[17] MacKenzie, W.H., & Mahony, C.R. (2021). An ecological approach to climate change-informed tree species selection for reforestation. *Forest Ecology and Management*, 481, article number 118705. doi: 10.1016/j.foreco.2020.118705.
[18] Moroz, V., & Nykytiuk, Y. (2020). Carbon absorption ability of pine forest plantations in Volyn Polissya. *Scientific Horizons*, 86(1), 61-70. doi: 10.33249/2663-2144-2020-86-1-61-70.
[19] Moroz, V., Stasyuk, N., & Tymoshenko, L. (2021). Peculiarities of growth, development and climate-stabilizing significance of fir plantations of the Ukrainian Carpathians. *Sustainable Use of Natural Resources*, 3, 68-77. doi: 10.33730/2310-4678.3.2021.247139.
[20] North, M.P., *et al.* (2019). Tamm Review: Reforestation for resilience in dry western US forests. *Forest Ecology and Management*, 432, 209-224. doi: 10.1016/j.foreco.2018.09.007.
[21] Petráš, R., Mecko, J., Krupová, D., Slamka, M., & Pažitný, A. (2019). Aboveground biomass basic density of softwoods tree species. *Wood Research*, 64(2), 205-212.
[22] Pilarek, Z., Gornowicz, R., & Galazka, S. (2007). Biomass of pine saw timber stands growing on the fresh mixed coniferous site. *Acta Scientiarum Polonorum. Silvarum Colendarum Ratio et Industria Lignaria*, 6(2), 79-85.
[23] Repáč, I., Belko, M., Krajmerová, D., & Paule, L. (2021). Planting time, stocktype and additive effects on the development of spruce and pine plantations in Western Carpathian Mts. *New Forests*, 52, 449-472. doi: 10.1007/s11056-020-09804-3.
[24] Riechelmann, D.F., Albert, J., Britzius, S., Krebsbach, F., Scholz, D., Schenk, F., Jochum, K.P., & Sirocko, F. (2023). Bioproductivity and vegetation changes documented in Eifel maar lake sediments (western Germany) compared with speleothem growth indicating three warm phases during the last glacial cycle. *Quaternary International*, 673, 1-17. doi: 10.1016/j.quaint.2023.11.001.
[25] Shvidenko, A., Lakyda, P., Schepaschenko, D., Vasylyshyn, R., & Machuk, Y. (2014). *Carbon, climate, and land-use in Ukraine: Forest sector*. Kiev: National University of Life and Environmental Sciences of Ukraine.
[26] Stanturf, J.A., Perdue, J.H., Young, T.M., Huang, X., Guo, Z., Dougherty, D., & Pigott, M. (2019). A spatially explicit approach to modeling biological productivity and economic attractiveness of

short-rotation woody crops in the eastern USA. *Energy, Sustainability and Society*, 9, article number 28. doi: 10.1186/s13705-019-0211-6.

[27] Sukhbaatar, G., Ganbaatar, B., Jamsran, T., Purevragchaa, B., Nachin, B., & Gradel, A. (2020). Assessment of early survival and growth of planted Scots pine (*Pinus sylvestris*) seedlings under extreme continental climate conditions of northern Mongolia. *Journal of Forestry Research*, 31, 13-26. doi: 10.1007/s11676-019-00935-8.

[28] Testolin, R., Dalmonech, D., Marano, G., Bagnara, M., D'Andrea, E., Matteucci, G., Noce, S., & Collalti, A. (2023). Simulating diverse forest management options in a changing climate on a *Pinus nigra* subsp. *laricio* plantation in Southern Italy. *Science of the Total Environment*, 857, article number 159361. doi: 10.1016/j.scitotenv.2022.159361.

[29] Ukrainian Hydrometeorological Centre. (n.d.). Retrieved from https://www.meteo.gov.ua/en/.

[30] Vlad, R., Constandache, C., Dinca, L., Tudose, N.C., Sidor, C.G., Popovici, L., & Ispravnic, A. (2019). Influence of climatic, site and stand characteristics on some structural parameters of Scots pine (*Pinus sylvestris*) forests situated on degraded lands from east Romania. *Range Management and Agroforestry*, 40(1), 40-48.

[31] Wang, T., Bao, A.M., Xu, W. Q., Zheng, G.X., Nzabarinda, V., Yu, T., Huang, X., Long, G., & Naibi, S.L. (2023). Dynamics of forest net primary productivity based on tree ring reconstruction in the Tianshan Mountains. *Ecological Indicators*, 146, article number 109713. doi: 10.1016/j.ecolind.2022.109713.

[32] Wojtan, R., Tomusiak, R., Zasada, M., Dudek, A., Michalak, K., Wroblewski, L., Bijak, S., & Bronisz, K. (2011). Trees and their components biomass expansion factors for Scots pine (*Pinus sylvestris* L.) of western Poland. *Sylwan*, 155(4), 236-243.

[33] Zhou, B., Liao, Z., Chen, S., Jia, H., Zhu, J., & Fei, X. (2022). Net primary productivity of forest ecosystems in the southwest karst region from the perspective of carbon neutralization. *Forests*, 13(9), article number 1367. doi: 10.3390/f13091367.

Біопродуктивність соснових лісів Полісся

Віра Мороз

Кандидат сільськогосподарських наук, доцент
Західноукраїнський національний університет
46009, вул. Львівська, 11, м. Тернопіль, Україна
https://orcid.org/0000-0002-1457-4641

Анотація. Метою дослідження було визначення біопродуктивності соснових лісів Полісся та їх вуглецепоглинальної здатності залежно від вікової структури деревостанів.Дослідження проводилося на 15 експериментальних ділянках у Житомирській та Рівненській областях протягом весняно-літнього сезону 2023 року. Було здійснено вимірювання біометричних показників дерев, таких як діаметр на висоті 1,3 метра (DBH) та висота дерев, а також проведено аналіз зразків деревини для визначення фітомаси стовбура, кори та крони. Встановлено, що біопродуктивність значно зростає з віком: у молодих лісах (10-30 років) біомаса становила в середньому 25 т/га, у середньовікових (40-60 років) – 65 т/га, а у стиглих лісах (80-100 років) досягала 120 т/га. Кореляційний аналіз показав високу залежність біомаси від діаметра дерев та їхньої висоти, де найсильніший зв'язок виявлено між об'ємом стовбура та фітомасою деревини (r = 1,00). Вуглецепоглинальна здатність лісів також збільшувалася з віком: молоді ліси поглинали близько 12,5 т/га вуглецю, середньовікові – 32,5 т/га, а стиглі ліси – до 60 т/га. Крім того, дослідження виявило, що кліматичні фактори, такі як кількість опадів і середня температура, суттєво впливають на біопродуктивність. При зниженні кількості опадів нижче 550 мм на рік спостерігалося зниження біомаси на 15-20 %. Таким чином, результати підкреслюють важливість сталого управління сосновими лісами Полісся, враховуючи їхню роль у глобальних процесах фіксації вуглецю, що робить їх важливим інструментом для боротьби з кліматичними змінами та екологічними викликами

Ключові слова: екологія; фітомаса; кореляційний аналіз; лісокористування; вуглець