

Modelling above-ground phytomass of Scots pine stands and assessment of carbon accumulation across forest site types in the Ukrainian Polissya and its north-western outskirts

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Abstract

Under global climate change, forest ecosystems play an increasingly important role as carbon sinks, while the carbon accumulation capacity of Scots pine stands is strongly influenced by stand age, forest site conditions, and ecological status. Regionally adapted phytomass models are therefore required to improve carbon-stock assessment, support reforestation planning, and estimate potential losses caused by forest degradation, fires, and logging. This study aimed to develop models of the above-ground phytomass of Scots pine stands in the Ukrainian Polissya and its north-western outskirts, taking into account stand age, bioproductivity, and forest site type to assess their carbon accumulation potential. The research was conducted in 2023–2024 within the Volyn, Rivne, and Zhytomyr regions. It covered 302 temporary sample plots established in natural Scots pine stands of varying ages (8–100 years) in accordance with the national standard. The results showed that the average density of above-ground phytomass ranged from 160–180 kg·m⁻² in loamy sand infertile pine site types to 440–465 kg·m⁻² in moist fairly infertile pine site types, where middle-aged and mature high-yielding stands with high density and well-developed crown mass predominate. In fresh fairly infertile pine site types, phytomass was 310–345 kg·m⁻², while in dry fairly infertile pine site types, it was 190–230 kg·m⁻². Mathematical modelling enabled the construction of logarithmic regression models describing the relationship between stand age and the specific phytomass conversion coefficients for wood, bark, and crown. It was established that conversion coefficients decrease with stand age, reflecting the regular reduction in the specific mass of individual fractions. The practical significance of these results lies in their application to spatial planning of reforestation, assessment of carbon potential, and the development of climate-oriented forest policy in conditions similar to those of the Ukrainian Polissya and its north-western outskirts.

Key words: carbon sequestration, fairly infertile pine site types, logarithmic relationships, *Pinus sylvestris* L., stand bioproductivity.

Introduction

Forest ecosystems increasingly function as carbon sinks under global climate change. In Scots pine stands, carbon accumulation depends on age, site type, and ecological condition. Regionalised phytomass models for Ukrainian Polissya and its north-western outskirts are needed to improve carbon-stock prediction, reforestation planning, and assessment of losses from disturbance, fires, and logging. For brevity, the term 'pine' is used throughout this paper to refer to Scots pine (*Pinus sylvestris* L.).

According to the current geobotanical regionalisation of Ukraine, the study area lies predominantly within the Polissian subprovince of the Eastern European (Sarmatian) province in the European broadleaved-forest region (Didukh and Vashenyak 2013). This framework differentiates regional units according to vegetation composition and ecological conditions and therefore provides an appropriate basis for spatial stratification of forest biomass models. Studies conducted in Right-Bank and Central Polissia further show that above-ground phytomass changes systematically during autogenic succession and vegetation recovery, generally following logarithmic trajectories, whereas external disturbance reduces the rate of phytomass accumulation.

Moroz and Tymoshenko (2025) studied Polissia Scots pine stands' energy and bio-productive capacity. The authors calculated biomass energy efficiency coefficients and discussed the relationship between productivity and stand age. Lovynska (2021) modelled Scots pine bioproductivity in Ukraine's Ravine Steppe. The study compared stand ecotype-specific modelling methodologies to find efficient growth parameters. Zadorozhniuk (2023) used

UAV stereophotogrammetry to catalogue Scots pine stands. The author found that forest mensuration indicators were highly accurate and that the use of UAV data greatly reduced fieldwork requirements. An earlier fundamental contribution was made by Khomiak et al. (2019), who investigated above-ground phytomass dynamics during autogenic ecosystem succession and demonstrated its relationship with successive changes in vegetation structure and ecosystem development. Khomiak et al. (2024) used phytomass to monitor vegetation cover and restore degraded ecosystems. The findings provided a basis for the adaptive management of natural areas. Aguirre et al. (2021) constructed stand-level biomass models for the main Spanish Scots pine species. The scientists verified the models using a large mensuration data sample, improving carbon stock forecasts. Jilo et al. (2025) developed above-ground biomass models for southern Ethiopia's Borana forest's primary tree species. They found significant biomass heterogeneity among species and showed how stem density affects model accuracy.

Puletti et al. (2025) used drone-based laser scanning to estimate biomass in beech forests using 3D crown metrics. The approach reduced uncertainties associated with stand heterogeneity. The approach reduces stand heterogeneity mistakes. Allometric models for individual *Eucalyptus saligna* Sm. trees in young Ecuadorian plantations were developed by Ramos-Veintimilla et al. (2025). The authors found that tree age and diameter were crucial to the accuracy of local models. Different Brazilian savanna plant types affect soil carbon, nitrogen, and phosphorus levels, according to Lacerda et al. (2025). The results showed that structural phytomass characterisation

and biogeochemical analysis are needed to quantify carbon flows. Balestra et al. (2024) estimated urban tree carbon stocks using spherical photography and UAV data. The authors showed that this green planning method works in cities. The assessment of scholarly sources revealed the importance of building adaptive models for measuring above-ground phytomass of forest stands, particularly Scots pine, for ecological monitoring, forest management, and climate change policy. Combining classical mensuration methods with remote sensing and machine learning has been shown to work internationally and nationally.

This study aimed to model the above-ground phytomass of Scots pine stands, taking into account stand age, bioproductivity, and forest site type to assess their carbon accumulation potential. To achieve this aim, the following objectives were set: to analyse the influence of ecological conditions on the phytomass of Scots pine stands; and to develop mathematical models for predicting above-ground phytomass depending on site conditions and tree morphometric parameters.

Materials and Methods

The investigation of above-ground phytomass of Scots pine stands was carried out in 2023–2024 within the Ukrainian Polissya and its north-western outskirts, in the territories of Volyn, Rivne, and Zhytomyr regions. Fieldwork was conducted in 25 state forestry enterprises representing geobotanically comparable territories characterised by similar edaphic and forest site conditions. Plot stratification was interpreted within the Polissian subprovince of the Eastern European (Sarmatian) province, following the geobotanical

regionalisation of Didukh and Vashenyak (2013). The sample included enterprises from Volyn, Rivne, and Zhytomyr regions, as well as selected forestry enterprises in Kyiv Region (Ivankiv, Poliskyi, Teteriv) and Chernihiv Region (Horodnia, Dobrianka, Koriukivka, Nizhyn) (Fig. 1). Their inclusion was necessary to ensure complete typological stratification of stands by site conditions, which enabled representative data collection and improved the reliability of the biomass models developed. In total, 302 sample plots were established, distributed among enterprises in accordance with the presence of Scots pine stands representing typical age groups. Fieldwork was conducted during the spring–summer period of each year (May–August), corresponding to the phase of active vegetation in the stands. Although conducting the surveys within the growing season improved the comparability of measurements, some intra-seasonal variation in crown phytomass may have remained. In particular, needle biomass may fluctuate between May and August because of the development of current-year needles and the gradual shedding of older needle cohorts. Since crown phytomass was estimated indirectly from stem mass using a generalised conversion relationship rather than through separate measurements of branches and needles at each sampling date, these seasonal changes were not explicitly represented. Consequently, crown and total above-ground phytomass may have been slightly overestimated or underestimated depending on the sampling date, whereas wood and bark estimates were expected to be less sensitive to seasonal variation. Crown phytomass values should therefore be interpreted as estimates representative of the active growing season rather than as season-independent values.

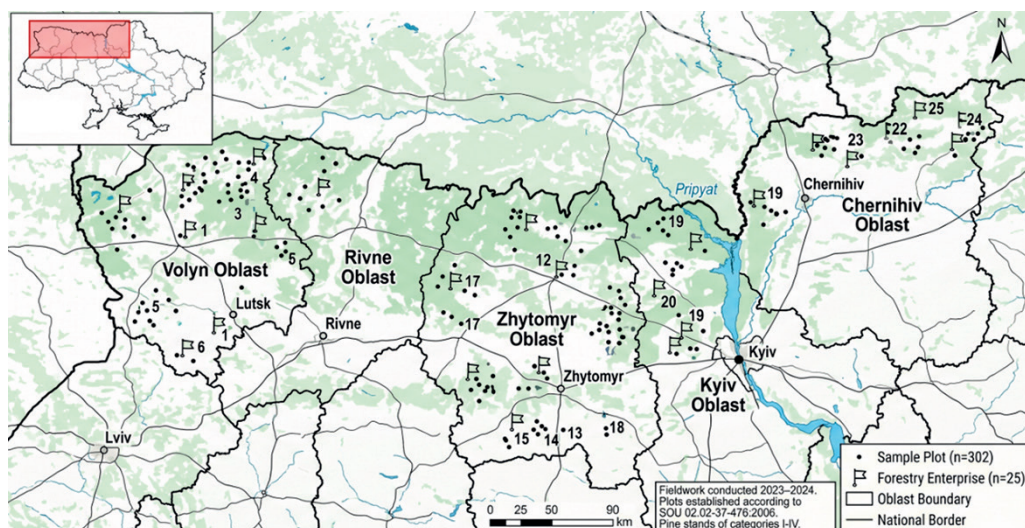


Fig. 1. Geographical location of sampling sites ($n=302$) and forestry enterprises within the Ukrainian Polissya and its north-western outskirts.

Source: compiled by the authors.

The selection of 25 state forestry enterprises for fieldwork was based on a set of criteria. First, the presence of extensive Scots pine stands (over 500 ha) was taken into account to ensure a representative sample for modelling. The sample included enterprises covering the main forest site types of the Ukrainian Polissya and its north-western outskirts – fresh fairly infertile pine site types, moist fairly infertile pine site types, and fairly fertile site types – as well as areas with typical and degraded stands, allowing assessment of the full range of carbon productivity. A mandatory condition was the availability of up-to-date forest management documentation, revised after 2015 (State Agency of Forest Resources of Ukraine ... 2024). Logistical accessibility for repeated surveys and spatial stratification was also considered. In cases where enterprises were partly located outside the Ukrainian Polissya and its north-western outskirts, the decisive factor was the similarity of site types

to those typical of the study region, along with the administrative structure of enterprises encompassing adjacent natural-geographical zones.

The distribution of sample plots was determined by the area of Scots pine stands within each enterprise, site accessibility, and representativeness of forest site types. Minor variation in the number of plots (from 8 to 18) did not affect the results, as the models were developed with typological stratification ensured (Table 1).

The study used a sample of 302 temporary sample plots established in accordance with the requirements of the national standard SOU 02.02-37-476:2006 'Forest Management Sample Plots. Establishment Methodology' (State Agency of Forest Resources of Ukraine ... 2024). Each plot had an area of 0.05 ha (radius – 12.62 m). On each plot, all trees belonging to the main storey were recorded, with data on species, diameter at breast height (1.3 m), tree height, age, sanitary condi-

Table 1. Distribution of sample plots across forestry enterprises included in the study (2023–2024).

No.	Name of forestry enterprise	Number of sample plots	No.	Name of forestry enterprise	Number of sample plots
1	Volyn Forest Seed Centre	12	14	Narodytskyi	11
2	Volodymyr-Volynskyi	9	15	Novohrad-Volynskyi	14
3	Kovelskyi	17	16	Ovrutskyi	16
4	Liuboml'skyi	10	17	Olevskyi	12
5	Manevytskyi	18	18	Slovechanskyi Agroforestry Enterprise	13
6	Turiiskyi	11	19	Ivankivskyi	8
7	Baranivskyi	14	20	Poliskyi	9
8	Bilokorovytskyi	12	21	Teterivskyi	10
9	Horodnytskyi	13	22	Horodnianskyi	8
10	Yemilchynskyi	12	23	Dobrianskyi	8
11	Korostenskyi	15	24	Koriukivskyi	9
12	Zhytomyrskyi	17	25	Nizhynskyi	8
13	Malynskyi	16		Total	302

Source: compiled by the authors.

tion, and timber quality class. These specific mensuration parameters were used to represent the bioproductivity of the stands in the analysis. The total number of surveyed trees was 3624. Phytomass was calculated as the sum of the mass of all trees within the plot, converted to a per-unit-area basis. Calculations were performed using volume and biomass tables adapted to the conditions of Scots pine forests in the Ukrainian Polissya and its north-western outskirts. All procedures were carried out in compliance with SOU 02.02-37-476:2006, including requirements for plot size, location, marking, and the recording of survey parameters (State Agency of Forest Resources of Ukraine ... 2024).

Scots pine stands of categories I–IV were examined under moist, fresh, dry moderately infertile, and loamy-sand infertile site conditions. Forest site types were identified in the field using soil type, moisture level, dominant understorey

species, and herbaceous cover, following the Forest Fund of Ukraine classification, and were verified against forest management documentation and edaphic–vegetation indicators. Purposive sampling ensured representation of stand age (8–100 years), bioproductivity, and edaphic conditions. Bioproductivity was represented by density, diameter, and height. Plots were classified as young (8–20 years of age; 48 plots, 15.9 %), middle-aged (21–60 years of age; 128 plots, 42.4 %), premature (61–80 years of age; 78 plots, 25.8 %), and mature or overmature (81–100 years of age; 48 plots, 15.9 %). Middle-aged stands predominated, reflecting the regional age structure, while all site conditions were represented across the remaining age groups. Only structurally uniform, pure Scots pine stands containing at least 90 % Scots pine growing stock were included. Species composition was determined from forest inventory records, maps, crown projections, and field

verification. Plots were excluded if they showed pronounced vertical heterogeneity, admixture of other species above 10 %, thinning, logging, windthrow, or fire damage. Excluded plots accounted for approximately 12 % of the initially identified sites and were recorded separately to maintain a statistically consistent sample.

The above-ground tree phytomass included wood, bark, and crown components. The phytomass of wood and bark was estimated using the classical volume-density relationship described by Equation (1):

$$m = V \cdot \rho_{\text{base}}, \quad (1)$$

where: m is the component mass, kg; V is the volume, m^3 ; ρ_{base} is the basic density of wood or bark according to Buksha et al. (2019).

Crown phytomass (m_{crown}) was estimated indirectly as a function of stem mass (m_{stem}), using an equation validated by Buksha et al. (2019). Total tree phytomass (m_{total}) was calculated as the sum of the three fractions according to Equation (2):

$$m_{\text{total}} = m_{\text{wood}} + m_{\text{bark}} + m_{\text{crown}} \quad (2)$$

Specific phytomass conversion coefficients ($\text{t} \cdot \text{m}^{-3}$) were calculated individually for each sample plot. Carbon content was determined by multiplying by a coefficient of 0.5, and further converted to CO_2 using the ratio $1 \text{ t C} = 3.67 \text{ t CO}_2$. The carbon content in dry biomass was estimated using the mean coefficient of 0.5, corresponding to the weighted average carbon fraction in wood, in line with the methodological approaches of the IPCC (Eggleston et al. 2006) and consistent with the recommendations of the Food and Agriculture Organization of the United Nations (2020) for the temperate climate zone. Conversion to CO_2 equivalent was performed by multiplying by 3.67 – the molar ratio between the atomic mass of C (12) and CO_2 (44).

Although these coefficients are standard in international practice, they may vary slightly depending on tree age, tissue structure, and environmental conditions. However, for the sake of consistency within the sample and comparability of results, standard values were applied.

Mathematical modelling was performed using logarithmic regression models for each fraction, according to Equation (3).

$$y = a \cdot \ln(x) + b, \quad (3)$$

where: x is stand age, y is the phytomass conversion coefficient, and a and b are regression parameters. All calculations were performed in Microsoft Excel (Analysis ToolPak), including chart generation, coefficient estimation, calculation of coefficients of determination (R^2), and estimation of 95% confidence intervals for a and b . For the nine age-class mean values displayed in figures 3–5, the confidence intervals were calculated from the standard errors of the ordinary least-squares coefficients using a two-sided Student t critical value with $n-2$ degrees of freedom. Model adequacy was evaluated visually using the regression plots and numerically using R^2 .

Simulation modelling of phytomass losses was performed through scenario analysis using the mean above-ground carbon density for each forest site type (moist, fresh, and dry fairly infertile pine site types) and the corresponding distribution area within the region. For each site type, a hypothetical scenario of complete stand degradation was modelled, to estimate carbon losses (C_{loss} , $\text{t C} \cdot \text{ha}^{-1}$) and the associated foregone carbon dioxide uptake according to equations (4) and (5):

$$C_{\text{loss}} = S \cdot \rho C, \quad (4)$$

$$\text{CO}_2 = C_{\text{loss}} \cdot 3.67, \quad (5)$$

where: S is the area of the forest site

type, ha; pC is the mean carbon density, $t\ C\cdot ha^{-1}$; and 3.67 is the stoichiometric conversion factor from carbon to CO_2 .

This approach enables a quantitative assessment of the risks of reduced regional carbon potential due to degradation processes and helps identify the most vulnerable forest site types. The assessment of phytomass losses resulting from forest site type degradation was performed using simulation scenarios based on data on mean carbon density, the area of each forest site type, and CO_2 equivalents. Field surveys were conducted directly by the research team according to a unified methodology approved at the beginning of the field season, using current forest management documentation from enterprises as an auxiliary source for preliminary stratification of plots and verification of mensuration parameters. All field surveys were conducted in accordance with the ethical standards of ecological research. The study did not involve invasive intervention in natural objects, nor did it result in the destruction or damage of vegetation, and was carried out in compliance with current environmental legislation of Ukraine (Verkhovna Rada of Ukraine 1994) and Law of Ukraine No. 1264-XII 'On Environmental Protection' (Verkhovna Rada of Ukraine 1991). Sample plots were established without disturbing the soil cover or hydrological regime and without the use of chemicals or heavy machinery.

Results and Discussion

Field surveys of plots in the Ukrainian Polissya and its north-western outskirts revealed significant spatial differences in the structure and density of above-ground phytomass in Scots pine stands, depending on forest site type. The surveys covered stands growing in moist fairly infertile pine site types (V), fresh fairly infertile pine site types (S), dry fairly infertile pine site types (SD), and loamy sand infertile pine site types (P), located within Volyn, Rivne, and Zhytomyr regions (Table 2).

To visualise variability in above-ground phytomass density across forest site types, Figure 2 was constructed; the corresponding 95% confidence intervals are reported numerically in Table 2.

The highest mean above-ground phytomass values were found in moist somewhat infertile pine site types with high soil moisture, fertility, and stand density (0.8–1.0). This group had 440–465 $kg\cdot m^{-2}$, using 295–310 $kg\cdot m^{-2}$, 35–42 $kg\cdot m^{-2}$ barkCrown phytomass is 90–105 $kg\cdot m^{-2}$. The prevalence of middle-aged and mature stands with high mean diameter (30–34 cm) and height (22–27 m) drove these high results.

The mean above-ground phytomass density was 310 to 345 $kg\cdot m^{-2}$ in fresh rather infertile Scots pine site types, which cover the most forest acreage in the region. The phytomass structure was better

Table 2. Mean phytomass density by forest site type with 95% confidence intervals.

Forest site type	Mean phytomass, $t\cdot ha^{-1}$	Standard deviation	Number of plots	Lower 95% CI	Upper 95% CI
Moist fairly infertile pine site type	156.4	18.7	62	151.7	161.1
Fresh fairly infertile pine site type	132.7	15.2	78	129.3	136.1
Dry fairly infertile pine site type	118.5	14.8	85	115.4	121.6
Loamy sand infertile pine site type	95.3	12.9	52	91.8	98.8

Source: compiled by the authors.

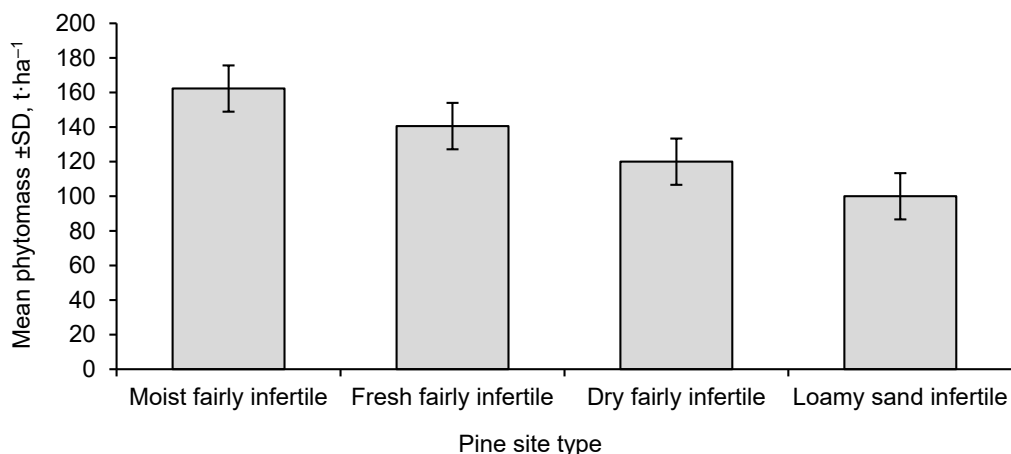


Fig. 2. Distribution of above-ground phytomass density in Scots pine stands by forest site type in the Ukrainian Polissya and its north-western outskirts.

Source: compiled by the authors.

balanced in these stands: wood – 205–225 kg·m⁻², bark 25–32 kg·m⁻² and crown 80–90 kg·m⁻². The stands were mostly middle-aged, with 0.6–0.8 stand density and 26–29 cm stem diameters. Phytomass density was much lower in dry, infertile pine sites on loamy sand soils with low rainfall. Means were 190–230 kg·m⁻², 120–145 kg·m⁻², bark 15–20 kg·m⁻² and crown 50–65 kg·m⁻². Dry, infertile pine sites had lower stand density (0.4–0.6) and growth. A large number of plots had young and low-productivity middle-aged stands. Infertile pine site types on loamy sand soils had the lowest phytomass, 160–180 kg·m⁻². They were dominated by thin-stemmed trees 18–22 cm wide and 12–16 m tall. Crown fraction of total phytomass was higher (up to 35 %), indicative of young or sparse stands.

Overall, a clear trend of decreasing phytomass was observed from moist to dry forest site types. Statistical comparison of mean values indicated a high degree of variability in above-ground biomass across the study region. The absolute

difference in phytomass density between moist fairly infertile pine site types and dry fairly infertile pine site types exceeded 280 kg·m⁻², highlighting the critical reduction of bioproductive potential under degraded conditions. These findings are consistent with the results of Tabacchi et al. (2011), who developed equations for predicting tree volume and phytomass for major tree species in Italy, taking into account mensuration data and site types. Their study emphasised that model accuracy improves significantly when stratified by forest site conditions, which aligns fully with the approach implemented in the present study.

Representative sample plots from different forest site types were evaluated to verify data and field observations. On a 0.05 ha plot in damp very infertile pine sites (V), 62 Scots pine trees had a mean diameter of 24.1 cm, stand density of 0.82, and average height of 21.3 m. Fresh sites (S) had 58 trees (21.7 cm; 0.76; 20.1 m). Density dropped to 47 trees (18.5 cm; 0.68; 18.2 m) in dry sites (SD)

and 43 in the least productive loamy sand sites (P). Biomass estimations were accurate since forest management paperwork corroborated these measurements. Field and statistical research led to regression models relating above-ground phytomass to age, diameter, and stand density. Age was the main factor, while diameter and density combined. Puls et al. (2024) stressed biomass density for carbon balance. The wood phytomass conversion coefficient for the nine age-class mean values in Fig. 3 follows the logarithmic equation $y = -0.08839 \ln(x) + 0.88631$ ($R^2 = 0.998$). In the 95% confidence interval, coefficient a ranged from -0.09234 to -0.08444 , whereas coefficient b ranged

from 0.87045 to 0.90218 . Between 20 and 100 years, the coefficient dropped from 0.62 to $0.48 \text{ t} \cdot \text{m}^{-3}$. Variability excluded younger stands. Socha et al. (2021) also stressed the importance of age and site characteristics in biomass modelling.

For the nine age-class mean values displayed in Figure 4, the bark conversion coefficient followed the logarithmic equation $y = -0.02207 \ln(x) + 0.15965$ ($R^2 = 0.989$). The 95% confidence interval was -0.02415 to -0.02000 for coefficient a and 0.15133 to 0.16797 for coefficient b . The negative age coefficient confirms the gradual decline in specific bark mass as stands mature.

For the nine age-class mean val-

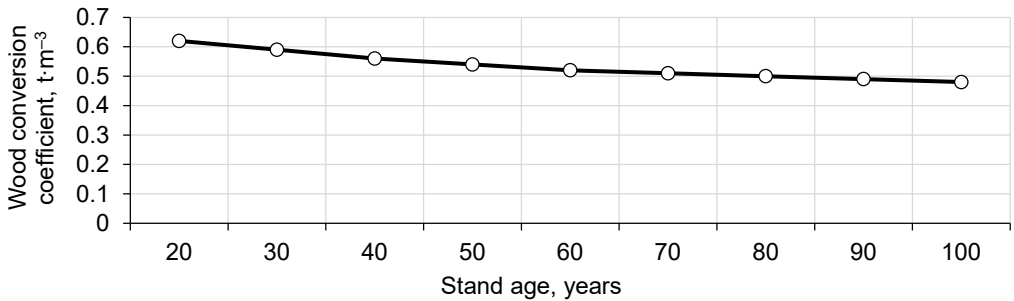


Fig. 3. Dependence of the wood conversion coefficient on stand age.

Source: compiled by the authors.

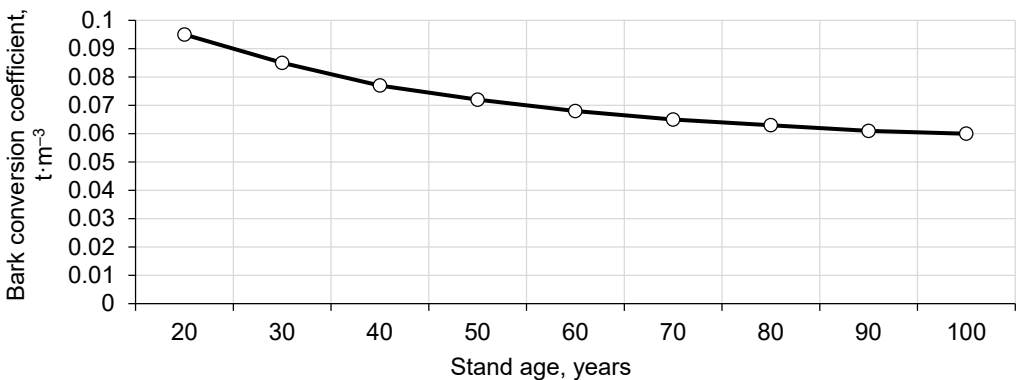


Fig. 4. Dependence of the bark conversion coefficient on stand age.

Source: compiled by the authors.

ues displayed in Figure 5, crown phytomass followed the logarithmic equation $y = -0.06529 \ln(x) + 0.40703$ ($R^2 = 0.995$). The 95% confidence interval was -0.06927 to -0.06132 for coefficient a and 0.39109 to 0.42297 for coefficient b . The age-related change in the crown conversion coefficient, from 0.210 to $0.109 \text{ t} \cdot \text{m}^{-3}$, indicated a gradual decrease in the proportion of the crown in total above-ground phytomass as trees matured.

All derived models demonstrated a high correspondence with the age-class mean values displayed in the figures ($R^2 = 0.989\text{--}0.998$). Reporting the regression equations and 95% confidence intervals in the text complements the graphical presentation without overcrowding figures 3–5. Thus, the logarithmic regression models based on Equation (3) confirmed the suitability of the modelling approach for predicting the component structure of phytomass according to stand age and other mensuration parameters, which is crucial for assessing the bioproductive potential of Scots pine stands in the region.

The findings agree with previous research. Segtowich et al. (2025) showed rapid Scots pine biomass reallocation after thinning, particularly in crowns, supporting crown-based productivity assessment. Temesgen et al. (2015) found that localised biomass models outperform uni-

versal models when adapted to climatic and edaphic conditions. Spatially adapted approaches are also supported by Oehmcke et al. (2022), who applied deep learning to three-dimensional point clouds, and by Puliti et al. (2021), who combined field measurements with Sentinel-2 and Landsat 8 data. Uller et al. (2021) likewise demonstrated that regional growth-form differences improve model performance.

Above-ground Scots pine phytomass in the Ukrainian Polissya and its north-western outskirts stores 68.2 million tonnes of carbon across 1055.8 thousand hectares (Moroz et al. 2020). Young stands store 0.84 million tonnes, stands aged 21–40 – 3.49 million, and stands aged 41–60 – 34.4 million tonnes. The latter value mainly reflects their extensive area rather than maximum productivity. Premature stands store 23.4 million tonnes but have the highest density, $8.6 \text{ kg} \cdot \text{m}^{-2}$. Mature stands retain 6.1 million tonnes at $7.5 \text{ kg} \cdot \text{m}^{-2}$. Carbon density exceeds $9 \text{ kg} \cdot \text{m}^{-2}$ on moist sites and declines to $4\text{--}5 \text{ kg} \cdot \text{m}^{-2}$ on dry sites, confirming age- and density-related carbon dynamics (Anderson et al. 2023).

Simulation modelling indicates risks to carbon balance under forest degradation. Dry fairly infertile pine sites (211.3 thousand ha) could lose 10.3 million tonnes of carbon, equivalent to 37.8 million tonnes of CO_2 . Fresh fairly infertile sites (304.3

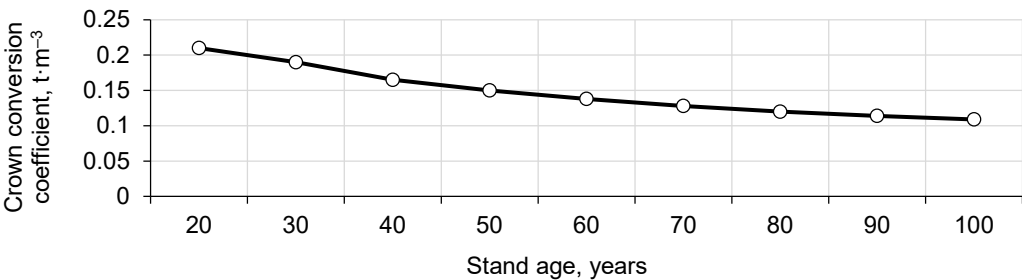


Fig. 5. Dependence of the crown conversion coefficient on stand age.

Source: compiled by the authors.

thousand ha) face the greatest losses: 23.2 million tonnes of carbon and 85.1 million tonnes of CO₂. Moist fairly infertile sites (113.5 thousand ha) could lose 14.2 million tonnes of carbon and 52.1 million tonnes of CO₂ because of their high biomass density.

These results confirm the need to preserve productive forest types. Cudjoe et al. (2025) showed that structural disturbances reduce long-term carbon accumulation, while Muukkonen and Mäkipää (2006) linked biomass to site moisture. Complete degradation could cause losses of 47.7 million tonnes of carbon and approximately 175 million tonnes of foregone CO₂ sequestration, exceeding 70 % of regional carbon stocks and potentially transforming forests from sinks into emission sources. Salekin et al. (2024) stressed that no single species ensures maximum carbon storage under stress. The findings support SDG 13 and SDG 15 (United Nations n.d.) and the Paris Agreement (UNFCCC n.d.). Restoration should prioritise moist fairly infertile sites, whose phytomass exceeds 9 kg·m⁻², while accounting for environmental variability (Huang and Lu 2025).

Fresh fairly infertile site types, which are the most extensive, also require priority attention, particularly in degraded areas. Restoration strategies should consider mixed Scots pine–birch stands and, where edaphic conditions are suitable, Scots pine–oak mixtures. In Ukrainian Polissia, Scots pine–birch stands containing 10–20 % silver birch have been shown to combine higher productivity with improved biodiversity and resilience relative to pure Scots pine stands, while studies of Scots pine–oak mixtures indicate complementary growth responses and sustained carbon sequestration potential (Tkach et al. 2022). The exact

species proportions should therefore be selected according to soil fertility, moisture regime, and management objectives rather than applied uniformly. In contrast, dry fairly infertile site types should not be prioritised for large-scale restoration due to their low productivity and vulnerability. However, targeted interventions, including drought-resistant Scots pine provenances and soil stabilisation measures, may help prevent further degradation. Bojórquez et al. (2025) demonstrated that integrating field and spectral data can improve biomass estimation even in low-productivity systems, suggesting potential methodological improvements for these areas.

Middle-aged stands represent the most significant carbon reservoir and should be protected from premature harvesting. Management should focus on maintaining stand density, minimising disturbances, and preserving hydrological balance. Dong et al. (2023) also highlighted the benefits of integrating ground-based and remote sensing data for improving biomass and carbon estimates in complex forest systems. In conclusion, effective forest management in the Ukrainian Polissya and its north-western outskirts requires a shift from area-based approaches to strategies focused on stand quality, productivity, and long-term carbon stability. Integrating modelling, empirical data, and risk assessment is essential for developing adaptive, climate-oriented forest policies that ensure sustainable carbon sequestration and ecosystem resilience.

Conclusions

The study demonstrated that site-specific edaphic conditions, stand age, and productivity strongly influence above-ground phytomass in Scots pine stands of the

Ukrainian Polissya and its north-western outskirts. Phytomass density declined from moist to dry sites, ranging from 440–465 kg·m⁻² in moist moderately infertile pine sites to 160–180 kg·m⁻² in loamy-sand infertile sites. Middle-aged and premature stands on moist soils with high density showed the greatest bioproductivity. Using data from 302 temporary sample plots, logarithmic models were developed for age-related changes in wood, bark, and crown phytomass. The models showed high explanatory power ($R^2 = 0.989\text{--}0.998$) and narrow 95% confidence bands. Biomass structure changed with age through declining specific crown and bark mass and an increasing wood proportion.

Above-ground Scots pine phytomass stored an estimated 68.2 million tonnes of carbon, including 34.4 million tonnes in stands aged 41–60. Degradation scenarios indicated approximately 175 million tonnes of foregone CO₂ sequestration. The models may support carbon-stock assessment, environmental monitoring, restoration planning, and climate-oriented forest management. Limitations include the exclusion of below-ground biomass, decomposition, and seasonal variation. Future studies should standardise sampling dates, quantify branch and needle biomass separately, and incorporate roots, soil carbon, management, and climate effects into landscape-scale spatial databases.

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