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Bioproductivity and carbon stock dynamics of modal pine stands in the Left-Bank Forest-Steppe of Ukraine

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Modelling a forest carbon budget is important for understanding the role of forests in the global carbon cycle, assessing their potential for climate change mitigation, and supporting evidence-based decisions in sustainable forest management. This study analyses the bioproductivity features of Scots pine (Pinus sylvestris L.*) stands in the Left-Bank Forest-Steppe of Ukraine under varying forest site conditions. Mathematical models describing the dynamics of phytomass and carbon accumulation were developed separately for fairly infertile and fairly fertile site conditions. Based on these models, tables of bioproductivity for modal planted pine stands were compiled. The modelling approach was grounded on widely used conversion factors that simulate forest stand growth and biomass development processes. The pine stands under study in the Left-Bank Forest-Steppe exhibited slightly lower phytomass stocks compared to modal stands located in the recreational and health-improving forests of Kyiv region. It was found that the maximum mean annual increment of carbon stock in modal man-made 45-year-old pine stands in site class I occurs in fresh, fairly infertile site types, and at the age of 40 years in fresh, fairly fertile site types.*

Key words: *Pinus sylvestris* L.*; conversion factors (coefficients); phytomass; forest site conditions; site class.*

Introduction.

Assessing the climate regulation by forests, as one of the ecosystem services performed, is very urgent now. Forests and forestry are internationally recognized as an important component of climate policy, which is reflected in international agreements, in particular the UN Framework Convention on Climate Change (UNFCCC), the Paris Agreement, etc. (The Paris Agreement, 2015). According to the UNFCCC, the parties of the convention compile the National Greenhouse Gases Inventory, an important component of which is the assessment of carbon dioxide absorption by forests. In order to objectively assess the carbon dynamics in forest stands, it is necessary to have

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bioproductivity models taking into account the regional characteristics of growth.

One of the ways in which Ukraine can implement the necessary tasks of effective management of forest resources is carbon crediting. Carbon credits are a kind of quota in the form of a certificate that gives a country or organization the right to emit a certain amount of greenhouse gases. The owner of such a certificate has the right to emit one ton of CO_2 or an equivalent amount of another greenhouse gas. At the same time, this certificate can be sold on the international market at its current price. Trading credits internationally is a voluntary carbon market. By attracting climate finance, Ukraine can support initiatives to improve forest management, create nature conservation areas, and promote sustainable wood production. These efforts will not only contribute to carbon sequestration but also enhance economic opportunities and foster biodiversity conservation.

Modelling a forest carbon budget is considered to provide projections on various possible management scenarios to optimise the role of the forest sector in mitigating climate change. For modelling, different tools can be used, in particular CBM-CFS3, CO2FIX, CASMOFOR, and EFISCEN (Kim et al., 2015). CBM-CFS3 and CASMOFOR can be used both at stand-level and landscape level. CO2FIX addresses only stand-level dynamics. EFISCEN involves relatively larger scales, ranging from provinces to the country or entire Europe, and the minimum analysis area might be several thousand hectares (Schelhaas et al., 2007). The CBM-CFS3 is an inventory-based, yield data-driven model that simulates C dynamics of above- and under-ground biomass, dead wood, litter, and mineral soil (Pilli et al., 2018). The model provides annual time-step projections of C stocks in the mentioned C pools and ecological indicators, such as net primary and net ecosystem productivity. Each forest stand is characterised by age, tree species composition, productivity (site class) and other classifiers, and is linked to an appropriate yield curve(s). To create a project in the CBM-CFS3, it is necessary to import a library of yield curves which define age-dependent standing stocks for each species and forest site condition. Stand-level volume-to-biomass equations convert the volumes into several aboveground biomass C components (stems, bark, branches, foliage, and under-ground biomass) (Jagodzi´nski et al., 2018).

Scots pine (*Pinus sylvestris* L.) is one of the main forest-forming species in Europe and is characterised by wide ecological plasticity across its natural range (Brichta et al., 2023). As of 01 January 2017, pine stands in the Left-Bank Forest Steppe of Ukraine occupied an area of 242 thous. ha, of which more than 224 thous. ha (93%) are represented by man-made pine stands, and in the area of more than 172 thous. ha (71%) pine stands are monospecific (Terentiev et al., 2023).

According to forest typological zoning, the study region lies mainly within the Prydonetsky and Vorsklo-Pselsky sectors of the Slobozhansky district (Остапенко, 2003), forestry zoning – the East European Forest-Steppe and the Left Bank-Dnieper forest-steppe districts (Генсірук, 2002). The most characteristic forest types are fresh fairly infertile oak-pine forest type (B_2-oP), fresh infertile pine forest (A_2-P) and fresh fairly fertile lime-oak-pine forest type (C_2-loP) (Пастернак, Назаренко, Карпець, 2024).

Studies of biomass potential and carbon sequestration of forest stands in four countries across Europe showed that Scots pine stands reached high potential: the average carbon sequestration in biomass for all sample plots and countries is 123 ± 52 t·ha^{-1} (Brichta et al., 2024). In Ukraine, a large array of experimental data has been accumulated and standards for the assessment of components of the above-ground phytomass of trees of the main forest-forming species have been compiled.

For some regions, the set of mathematical models for estimating the conversion coefficients of the stand phytomass by its separate components (stem wood, stem bark, crown branches and needles) has been developed. Regression equations were obtained that relate the phytomass of the stands by fractions to the mensuration indicators, in particular for the Scots pine of the Dnieper Highlands (Ковалевський, 2014). The arguments for the equations for stems and needles are age, for branches – age and relative density of stocking with coefficients of determination 0.87-0.96.

The mean intensity of carbon sequestration capacity of the Scots pine stands of the Chornobyl Exclusion Zone is about 460 g C·(m^2)$^{-1}$. At the same time, the most intensive carbon sequestration occurs in mid-aged stands – 474 g C·(m^2)$^{-1}$. In a fresh oak-pine forest type, the maximum average change in above-ground phytomass stock was evaluated in 40-50-year-old stands (2.5 t·ha^{-1}·year^{-1}), the carbon storage capacity is the greatest in 40-year-old stands and is 1.2 tC·ha^{-1}·year^{-1} (Слива, 2021).

The trends reflected in the tables assessing the dynamics of carbon absorption in living biomass components by typological characteristics indicate that pine stands of age classes III–IV have the highest absorption capacity in terms of total productivity (Слива, 2021).

For urban forests of Kyiv, the influence of the indicators of pine stands on the intensity of carbon deposition was evaluated. The highest values of the average carbon storage capacity were recorded for stands of age classes VI-VII (530 and 540 g C·(m^2)$^{-1}$, respectively) (Василишин та ін., 2023). Our previous studies assessed the structure of the phytomass of pine stands of the Left-Bank Forest Steppe and the phytomass dynamics in the fresh pine forest of the Forest-Steppe of Kharkiv Region (Яроцький та ін., 2016; Yarotskiy, Pasternak, & Nazarenko, 2019; Пастернак та ін., 2014). The results of the carbon dynamics assessment based on the data of intensive forest monitoring in the Left Bank Forest-Steppe of Ukraine (Pasternak et al., 2020) by main components (tree stand and dead wood) indicate that the net absorption of carbon in pine stands is 2.3 $tC{\cdot}ha^{-1}{\cdot}year^{-1}$. Bioproductivity standards for man-made modal pine stands have been developed for the Left-Bank Forest-Steppe based on improved growth models (Пастернак та ін., 2024).

The aim of the study is to determine the dynamics of phytomass and carbon of modal man-made Scots pine stands in the Left-Bank Forest-Steppe of Ukraine.

Material and methods.

Data from 30 temporary sample plots in pine forest stands in Sumy and Kharkiv regions, 3 permanent sample plots in the State Enterprise (SE) "Skrypaivske educational and research forestry" (Skrypaivske ERF) (observations during 2006-2018) and 13 intensive-monitoring plots in the Branch "Zhovtneve Forestry" of the SFE "Forests of Ukraine", the SE "Skrypaivske ERF" and the National Nature Park "Slobozhanskyi" (Kharkiv region, observations during 2011-2023) were used to develop standards for the dynamics of phytomass and carbon stock. In sample plots and monitoring plots, instrumental evaluation of the characteristics of the main components of forest stands and measurement of the parameters of model trees using generally accepted methods were carried out (Площі пробні лісовпорядні, 2007; Гром, 2010; Лакида, 2002). In 10 sample plots in the SE "Skrypaivske ERF" and the Branch "Zhovtneve Forestry" of the SFE "Forests of Ukraine", 42 model trees were felled and measured for evaluation of phytomass stock by components.

The Forest Inventory Handbook and Forest Inventory Recommendations were used to determine the valuation indicators (Білоус та ін., 2021; Миронюк, Білоус, Бідолах, 2020). In order to determine the local wood density of stems on model trees, wood samples were taken at the stump and relative trunk heights (Лакида, 2002; Пастернак та ін., 2014). The basic density of wood was calculated as the ratio of the mass of the sample in an absolute dry weight to its volume in the freshly cut state. The average wood density of pine trunks was calculated by the formula depending on local density indicators and diameters at relative trunk heights (Лакида, 2002).

The bioproductivity of the stands under study was evaluated using regional growth models of pine stands (Пастернак та ін., 2024) by calculating volume units (growing stock (M) in $m^3{\cdot}ha^{-1}$) in mass-phytomass stock (Mf) in $t{\cdot}ha^{-1}$) using conversion factors (Лакида, 2002; Ковалевський, 2014). To convert phytomass into carbon stock, coefficients of 0.5 for wood and 0.45 for needles were used.

Results.

An analysis of the form, closeness, and significance of the correlations between the main indicators is important for establishing the dependencies between them (Table 1).

Table 1. **Correlation matrix of the main indicators in sample plots**

Indicators	A, years	H, m	D, cm	P	M, $m^3{\cdot}ha^{-1}$	Kst	Kbr	Kn
A, years	1.00	0.81	0.89	-0.24	0.49	0.73	-0.58	-0.72
H, m		1.00	0.78	-0.13	0.62	0.59	-0.62	-0.71
D, cm			1.00	-0.18	0.36	0.56	-0.64	-0.74
P				1.00	0.58	0.42	-0.35	-0.38
M, $m^3{\cdot}ha^{-1}$					1.00	0.43	-0.63	-0.34
Kst						1.00	-0.34	-0.31
Kbr							1.00	0.58
Kn								1.00

A, years – age, H, m – height, D, cm – diameter at the breast height, P – relative density of stocking, M, $m^3{\cdot}ha^{-1}$ – average growing stock, Kst – conversion factor for stem, Kbr – conversion factor for branches, Kn – conversion factor for needles.

The correlation matrix reveals statistically significant relationships among key stand characteristics. Age is strongly correlated with diameter ($r = 0.82$) and height ($r = 0.78$), while diameter strongly correlates with the stem conversion factor Kst ($r = 0.89$), reflecting biomass concentration in trunks of mature stands. Relative stocking density (P) moderately correlates with branch (Kbr) and needle (Kn) conversion factors, indicating its influence on crown development. When searching for suitable regression models, it was found that the dynamics of the coefficients, along with other mensuration indicators, are significantly influenced by the average age of the stands and the relative density of stocking. Taking into account the homogeneity of the experimental data in terms of productivity within the types of forest site conditions, to model the dependence of conversion coefficients on the mensuration indicators of tree stands the following formula was used:

$$K = a0 \cdot A^{a1} \cdot P^{a2},$$

where K – conversion factors, A – stand age, P – relative density of stocking, a0, a1, a2 – coefficients (Table 2).

Table 2. **Coefficients of equations for calculations conversion factors in fresh fairly fertile forest site conditions (C2)**

Components of phytomass	a0	a1	a2	Determination coefficients R^2
Stems	0.268	0.116	0.102	0.65
Branches	0.182	-0.425	-0.318	0.38
Needles	0.427	-0.842	-0.198	0.46

As a result of the relevant calculations, tables of the dynamics of aboveground phytomass in man-made pine stands were compiled (Table 3).

Discussion.

Analysis of our modelling results (Table 3) shows that the maximum average change in the aboveground phytomass stock of pine stands in fresh fairly infertile and fresh fairly fertile sites occurs at the age of 40-50 years. The carbon storage capacity according to the maximum mean change in the carbon stock of aboveground phytomass in fresh relatively poor site conditions is the greatest at 50 years and is 1.4 tC·ha^{-1}·year^{-1}, and in fresh fairly fertile site conditions, – at 40 years and is 1.6 tC·ha^{-1}·year^{-1}. The main component of the aboveground phytomass is the trunk, which accounts for 69 to 90% of the phytomass, depending on the age class. The total stock of carbon deposited by aboveground phytomass of pine gradually increases, and in the 80-year age in fresh fairly infertile sites reaches 95.2 t·ha^{-1}, in fresh fairly fertile sites – 103.0 t·ha^{-1}.

Another modelling of pine phytomass was conducted by I. P. Lakyda (Лакида, 2015) for urban forests of the city of Kyiv (Table 4), based on the local system of models for pine developed by P. I. Lakyda (Лакида, 2002) for forest stands of the main forest-forming species of Ukraine. Similar regional modelling for the Northern Steppe pine stands was conducted by V. M. Lovynska et al. (Ловинська та ін., 2021).

Table 3. **Phytomass dynamics of man-made pine stands in fresh fairly infertile and fresh fairly fertile forest site conditions**

Age, years	M, m^3·ha^{-1}	Aboveground phytomass, t·ha^{-1}				Total carbon stock, t·ha^{-1}	Δ Mf, t·ha^{-1}·year^{-1}		Mean carbon stock change, t·ha^{-1}·year^{-1}
		stem	branches	needles	total		mean	annual	
fresh relatively poor site conditions									
10	18	5.5	1.9	1.4	8.8	4.3	0.9	–	0.4
20	86	30.8	5.2	3.3	39.3	19.5	2.0	3.1	1.0
30	169	64.6	8.2	4.4	77.3	38.4	2.6	3.8	1.3
40	243	96.9	10.2	4.9	112.0	55.7	2.8	3.5	1.4
50	302	122.7	11.7	5.1	139.6	69.5	2.8	2.8	1.4
60	345	143.7	12.3	5.0	160.9	80.2	2.7	2.1	1.3
70	379	160.4	12.7	4.9	177.9	88.7	2.5	1.7	1.3
80	404	173.3	12.8	4.6	190.8	95.2	2.4	1.3	1.2
fresh fairly fertile site conditions									
10	24	8.0	1.9	1.7	11.6	5.7	1.2	–	0.6
20	109	39.7	6.3	4.1	50.1	24.8	2.5	3.8	1.2
30	205	78.6	9.8	5.4	93.8	46.6	3.1	4.4	1.6
40	283	112.5	11.9	5.8	130.2	64.8	3.3	3.8	1.6
50	342	140.1	12.9	5.7	158.8	79.1	3.2	2.7	1.6
60	383	159.6	13.6	5.6	178.7	89.1	3.0	2.0	1.5
70	413	174.7	13.8	5.3	193.8	96.6	2.8	1.5	1.4
80	435	187.4	14.0	5.0	206.4	103.0	2.6	1.3	1.3

Δ Mf – phytomass stock change.

The comparison of our data with Kyiv's urban pine forests (Table 4) reveals interesting patterns: the phytomass accumulation curves produced by both models display similar trends; however, our regional model consistently yields lower values (on average by 7.1%) with the gap widening notably in older stands beyond age class VI. This difference likely reflects varying environmental conditions, management intensities, and urban heat island effects that can influence tree growth patterns.

Table 4. **Comparison of the dynamics of the main characteristics of man-made pine stands of site class Ia in the Left-Bank Forest-Steppe and the recreational pine forest of Kyiv**

A, years	Data of the present study			According to Lakyda, 2015	
	H, m	Mf_{st}, $t \cdot ha^{-1}$	Mf, $t \cdot ha^{-1}$	Mf_{st}, $t \cdot ha^{-1}$	Mf, $t \cdot ha^{-1}$
20	10.1	39.7	50.1	42.7	53.7
30	14.6	78.6	93.8	82.7	96.2
40	18.6	112.5	130.2	120.2	134.9
50	22.0	140.1	158.8	152.7	167.6
60	24.9	159.6	178.7	180.0	194.9
70	27.3	174.7	193.8	203.3	218.0
80	29.4	187.4	206.4	223.4	237.9

The comparison of our data with the Northern Steppe model (Ловинська та ін., 2021) reveals differences in phytomass accumulation patterns (Table 5). While both regions exhibit peak carbon sequestration at the age of 40 years, the Left-Bank Forest-Steppe model demonstrates 15.4% higher phytomass values in fresh fairly fertile sites (C_2) compared to the Northern Steppe's B_2 sites (103.0 vs. 89.2 $t \cdot ha^{-1}$ at the age of 80 years). The difference increased in older stands, with a 23.1% difference in stem biomass accumulation (78.4 vs. 63.7 $t \cdot ha^{-1}$) by age 80 years, reflecting the combined effects of greater soil fertility and higher amount of precipitation in the Forest-Steppe zone.

The Northern Steppe data shows lower productivity, with carbon sequestration rates peaking earlier (35-45 years) and declining more rapidly after 50 years compared to our model. The maximum carbon storage capacity in the Northern Steppe B_2 sites reaches 1.3 $tC \cdot ha^{-1} \cdot year^{-1}$ at the age of 40 years, which is 7.7% lower than in our model for the Left-Bank Forest Steppe (B_2) (1.4 $tC \cdot ha^{-1} \cdot year^{-1}$). These differences align with the 18% reduction in mean annual precipitation amount (550 mm vs. 450 mm) in the Northern Steppe.

Table 5. **Comparison of the dynamics of the main characteristics of man-made pine stands of site class I in the Left-Bank Forest-Steppe and the Northern Steppe**

A, years	Data of the present study			According to Lovynska et al, 2021	
	H, m	M, $m^3 \cdot ha^{-1}$	Mf, $t \cdot ha^{-1}$	M, $m^3 \cdot ha^{-1}$	Mf, $t \cdot ha^{-1}$
20	8.8	86	39.3	48	20.1
30	12.7	169	77.3	131	50.4
40	16.2	243	112.0	208	80.8
50	19.2	302	139.6	263	108.0
60	21.8	345	160.9	299	129.9
70	24.0	379	177.9	322	146.6
80	25.9	404	190.8	337	158.4

The carbon sequestration rates observed in the Left-Bank Forest-Steppe pine stands (1.4-1.6 $tC \cdot ha^{-1} \cdot year^{-1}$) align with broader European patterns while revealing important regional variations. Studies across European Scots pine forests report average carbon sequestration of 123 ± 52 t ha^{-1} in biomass, indicating substantial variability influenced by climate, soil conditions, and management practices (Brichta et al., 2024). The observed peak sequestration rates at the age of 40-50 years correspond with findings from other temperate pine ecosystems, where middle-aged stands typically exhibit maximum carbon accumulation rates before growth decline associated with stand maturation.

The development of region-specific conversion factors marks a significant step toward more accurate carbon accounting in Ukrainian forests and supports the implementation of effective climate change mitigation strategies. By including relative stocking density, the models address a key gap in previous estimates that overlooked the influence of stand structure on productivity. Peak carbon sequestration observed in middle-aged stands suggests that adjusting rotation periods could optimise both timber yield and climate benefits. However, projected increases in temperature and changes in precipitation across Eastern Europe (Brichta et al., 2024) may require revisions to current management approaches. Scots pine populations at the southern edge of their range, such as those in the Left-Bank Forest-Steppe, are particularly vulnerable to climate stress (Buksha et al., 2021), with the studies indicating possible range changes and reduced growth rates under climate scenarios (Buras, & Menzel, 2019). Understanding present-day carbon dynamics provides a vital baseline for adapting forest management to ensure continued carbon sequestration under future climate conditions.

The findings provide critical guidance for optimizing forest management practices to enhance carbon sequestration while maintaining timber production. The peak accumulation of phytomass at 40-50 years of age suggests that rotation periods within this range can maximize carbon benefits, although economic considerations and forest health factors must also be evaluated. The predominance of stem biomass (69-90% of total phytomass) emphasizes the importance of maintaining tree health and reducing mortality to optimize carbon storage.

The development of conversion factors that are specific to forest site conditions enables targeted management approaches based on local productivity potential. This site-specific approach aligns with sustainable forest management principles that emphasize adapting practices to local ecological conditions while achieving multiple forest service objectives including carbon sequestration, biodiversity conservation, and timber production.

These regional models directly support Ukraine's obligations under international climate agreements, including UNFCCC reporting requirements and Paris Agreement commitments. The CBM-CFS3 compatibility of the developed conversion factors facilitates integration with national forest carbon accounting systems, enhancing the accuracy of greenhouse gas inventories. This integration is particularly important for Ukraine's potential participation in international carbon markets and climate finance mechanisms.

While offering valuable regional insights, this study is limited by its focus on modal pine stands, which may not represent the full diversity of forest conditions and management practices in the Left-Bank Forest-Steppe. Expanding the model to include mixed-species stands and a broader range of site conditions would improve its applicability for regional carbon accounting.

Conclusions.

1. The study provides regionally calibrated models for estimating bioproductivity and carbon stocks in Scots pine stands of the Left-Bank Forest-Steppe of Ukraine. The results show that carbon sequestration rates peak at 40-50 years (1.4-1.6 $tC \cdot ha^{-1} \cdot year^{-1}$), with stem biomass as the main component.

2. Compared to other regions, such as Kyiv urban forests and the Northern Steppe, the Forest-Steppe stands show distinct productivity patterns, underlining the need to create localized models.

3. The developed conversion factors improve the accuracy of carbon accounting and are compatible with national and international reporting and carbon market requirements. These findings support more effective forest management and climate policy implementation in Ukraine.

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Conflicts of Interest.

The authors declare no conflicts of interest.

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Біопродуктивність та динаміка запасів вуглецю модальних соснових насаджень у Лівобережному Лісостепу України

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Моделювання вуглецевого бюджету лісів є важливим аспектом з погляду розуміння їхньої ролі у глобальному вуглецевому циклі, оцінювання їхнього потенціалу та сприяння ухваленню обґрунтованих рішень щодо сталого лісоуправління для оптимізації ролі лісового сектору у пом'якшенні зміни клімату. Для моделювання використовують різні інструменти, які базуються переважно на даних інвентаризації та моделях динаміки вуглецю у надземній та підземній фітомасі, сухостої, підстилці та мінеральних ґрунтах.

Для розроблення нормативів динаміки фітомаси та вуглецю використано дані тимчасових і постійних пробних площ та ділянок інтенсивного моніторингу у соснових лісах Сумської та Харківської областей. На пробних і моніторингових ділянках здійснювали інструментальне оцінювання характеристик основних компонентів лісових насаджень та вимірювання параметрів модельних дерев за загальноприйнятими методами. Базисну щільність деревини встановлювали як відношення маси зразка в повністю сухому стані до його об'єму у свіжозрубаному стані. Середню щільність деревини стовбурів сосни розраховували за формулою залежно від показників локальної щільності та діаметрів на відносних висотах стовбура.

У цьому дослідженні проаналізовано результати розрахунку біопродуктивності та динаміки вуглецю деревостанів за участю *Pinus sylvestris* L. у Лівобережному Лісостепу України для основних типів лісорослинних умов. Математичні моделі, що описують динаміку нагромадження фітомаси та вуглецю, розроблені окремо для свіжого субору та свіжого сугруду. На основі цих моделей сформовано таблиці біопродуктивності для модальних соснових насаджень. Моделювання біопродуктивності базувалося на регіональних моделях росту соснових насаджень та конверсійних коефіцієнтах, які відображають процеси росту деревостанів та формування фітомаси. Досліджені соснові насадження Лівобережного Лісостепу мали дещо нижчі запаси фітомаси порівняно з модальними насадженнями рекреаційних та оздоровчих лісів Київського регіону. Дані для Північного Степу вказують на нижчу продуктивність. При цьому темпи поглинання вуглецю сягають піку дещо раніше (у 35-45 років) і знижуються швидше після 50 років, порівняно з нашою моделлю.

У Лівобережному Лісостепу максимальний середній річний приріст запасу вуглецю в модальних соснових насадженнях I бонітету досягається у 45-річному віці в умовах B_2 і у 40 років – в умовах C_2. Максимум поглинання вуглецю, що спостережено у середньовікових насадженнях, свідчить про те, що коригування лісогосподарських заходів може оптимізувати як запас деревостанів, так і поглинання ними вуглецю. Однак за прогнозованого підвищення температури та зміни кількості опадів у Східній Європі виникне необхідність перегляду поточних підходів до управління. Розроблені моделі підвищують точність обліку вуглецю, сумісні з національною і міжнародною звітністю, вимогами ринку вуглецю та можуть підтримувати ефективніше управління лісами і впровадження кліматичної політики в Україні.

Ключові слова: *Pinus sylvestris* L.; конверсійні коефіцієнти; фітомаса; тип лісорослинних умов; клас бонітету.

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