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Validation of a biomass based model for assessing forest ecosystem services: a case study of Feofania Park

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ABSTRACT

The study presents estimates of the dynamics of the urban forest stand ecosystem services in Feofania Park, based on forest live biomass assessment models and data from forest management planning. The study aimed to compare the model approach for forest live biomass assessment with permanent sample plot data and to investigate the possibility of forest ecosystem service assessment based on forest biomass models. The fieldwork was conducted on four permanent sample plots in urban forests, established in 2016 and 2017. The age range of the research stands from 80 to 180 years. Each sample plot determined the species composition of forest stands and the status of trees by measuring and surveying in kind, with a division into live and dead biomass. The peculiarities of the redistribution of trees by vitality status in 2023 changed to some extent due to an increase in the number of dead trees (snags). It has been established that the highest current increment of live biomass is observed on the permanent sample plot with a structurally complex stand, featuring 180–190-year-old oak trees in the first canopy layer. For each permanent sample plot, a comparison of biomass indicators for the tree stand was made using fieldwork and model-based data. The relative deviation in the overall estimate of forest live biomass using the model approach ranged from -39% to -2% when comparing estimates from permanent sample plots collected during fieldwork from 2016 (2017) to 2023. This suggests the potential applicability of using a model to estimate the biomass of each urban forest plot in the park. The assessment of the biomass of the park's forest stands served as the basis for calculating the volumes of carbon storage, produced oxygen, and accumulated energy.

KEY WORDS

forest stand, snags, live biomass, carbon storage, oxygen production, accumulated energy

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INTRODUCTION

To address the risks posed by climate change, the Paris Agreement provides the central international policy framework guiding global emission-reduction efforts and defining the contribution of land-use sectors, including forestry, to climate change mitigation (United Nations 2015). International environmental initiatives aim to consolidate global efforts to implement measures that preserve the environment, particularly by reducing greenhouse gas emissions and mitigating climate change. Achieving zero emissions and minimising the use of fossil fuels are most effectively realised by expanding the use of renewable energy sources and fostering the development of a circular economy. These objectives align with the sustainable development goals for natural resource management, which include the balanced exploitation of forest resources (Gough et al. 2008) and the application of mechanisms for evaluating ecosystem services. A systematic analysis and the development of a comprehensive database to model the condition of forest ecosystems are essential for assessing the functions and services provided by forest stands. Moreover, the condition of natural and semi-natural ecosystems, along with their functions and services within urban environments, including urban forests and nature reserves, remains understudied in many regions.

Each object of the nature reserve fund is of unique importance, particularly for conserving biodiversity and unique ecosystems, comprehensive restoration of territories after man-made disasters and protection of natural landscapes under rapid urbanization. Forest management in the nature reserve fund faces numerous challenges that require scientific solutions. An example is the Chornobyl Radiation and Ecological Biosphere Reserve, where the critical impact of wildfires and other disturbances threatens sustainable forest development (Beresford et al. 2021; Matsala et al. 2021). Assessing ecosystem functions and services based on a comprehensive study of productivity enables us to draw basic conclusions about the state of forests and sustainable development.

As a modern megalopolis, Kyiv has integrated several forests, including rare forest biotopes (Didukh and Alioshkina 2012; Netsvetov et al. 2019), which are vital for providing ecosystem services and maintaining biodiversity (Radchenko et al. 2019; Koniakin and Gubar 2022). A detailed examination of biological productivity within these forests provides critical insights into the state and growth features of these forest stands. The endeavour to assess forest biological productivity and ecosystem services is crucial not only for understanding their current dynamics but also for addressing broader economic, ecological, social, and energy-related challenges (Brockerhoff et al. 2017). Furthermore, these assessments form a sound scientific foundation for national greenhouse gas accounting in the forest sector and thereby strengthen the ability to meet its post-Kyoto and subsequent international climate obligations related to carbon sequestration and mitigation in land-use systems (Pan et al. 2024). The assessment of ecosystem functions and services fundamentally involves examining forest biomass across various regions and conditions. This includes detailed studies on net primary production, live biomass, dead wood, and their dynamics (Keith et al. 2014). Forest live biomass is defined as the total mass of organic matter from all living plants within the ecosystem, quantified in units of absolute dry matter mass. This metric is crucial for evaluating and mapping the productivity of forested areas (Shvidenko et al. 2014). Furthermore, it serves as a foundation for assessing the ecological and resource potential of forests, particularly for understanding the environmental impacts of logging within forest stands. Tracking changes in live biomass is a critical component of environmental monitoring, especially in the context of urban forestry (Matsala et al. 2021) and when modelling forest productivity in response to global and local climate changes. These changes also play a significant role in evaluating forests' carbon storage functions (Bilous et al. 2019). A key objective is the regional and local assessment of tree stand live biomass dynamics and the carbon storage (Feshchenko and Bilous 2022; Feshchenko et al. 2023). This makes the study of biological productivity in forest stands within major cities and urban agglomerations particularly pressing. For sustainable regional development, it is crucial to maintain the continuous functioning of forest ecosystems and ensure the structural diversity of stands (Matsala et al. 2021). Long-term studies on the growth patterns and development of stands

(Schepaschenko et al. 2017), root systems (Guz 1996) and forest biological productivity (Lakyda et al. 2013; Shvidenko et al. 2014) have facilitated the development of mathematical models and standards to evaluate the live biomass components of reference plantations for the key forest species in Ukraine (Lakyda et al. 2011, 2013) and Northern Eurasia (Shvidenko et al. 2007). These models are instrumental in determining the dynamics of total live biomass in forest stands across Eastern Europe.

In Ukraine, a first forest inventory based on remote sensing data was conducted, including an assessment of forest biomass and carbon storage using a model-based approach (Myroniuk V. 2023). Nevertheless, before this study, such an approach had not been validated against data from permanent sample plots within Ukrainian forests.

While these models could also be applicable to urban forests and nature reserves, they have not yet been validated in these contexts. The main objective of this research is to validate the model assessments of live biomass and carbon storage against field tree surveys and evaluations on permanent sample plots (SP), with a focus on urban forests and nature reserves.

MATERIAL AND METHODS

The study was conducted in the urban forest stands of Feofania Park (Kyiv), located at the border between the forest-steppe and Polissia regions, vast forest areas in Eastern Europe. The Feofania Park is a structural part of the State Institution «Institute for Evolutionary Ecology of the National Academy of Sciences of Ukraine» (IEE). From 2016 to 2023, the number of live trees and snags (standing dead trees) on the SP was monitored. The IEE established these plots in 2016–017 (Schepaschenko et al. 2019).

Firstly, during 2011–2023 (Instructions for… 2006), we conducted a live biomass assessment of the stands according to forest inventory rules, utilising models (Shvidenko et al. 2007) and normative reference tables (Bilous et al. 2021). The productivity and carbon storage data were based on forest inventory results, the growing stock volume (over bark), and models developed by A. Shvidenko and co-authors (Shvidenko et al. 2007) for the forests in the European part of Eurasia. This approach includes the use of conversion coefficients (1), which represent the relationship between the mass of each component of live biomass (*Fi*) and the growing stock volume (over bark) (*M*):

$$R^i = \frac{F^i}{M} = f(T_j) \qquad (1)$$

where *Ri* is the conversion coefficient for component *i* (stem under bark, bark, stem over bark, leaves, branches), and *Tj* represents the parameters of the forest inventory.

Conversion coefficients are calculated according to the model (2) based on key forest inventory parameters, including age, site index (quality class), and stand density index (relative stocking) (Shvidenko et al. 2007):

$$R_{fr} = \frac{M_{fr}}{GS} = c_0 \cdot A^{c_1} \cdot SI^{c_2} \cdot RS^{c_3} \cdot exp(c_4 \cdot A + c_5 \cdot RS) \qquad (2)$$

where M_{fr} is the dry mass of a component of live biomass in $t \cdot ha^{-1}$, *GS* is the growing stock volume in a stand in $m^3 \cdot ha^{-1}$, *A* is the average age of a stand, SI is the code of site index (quality class), and RS is the relative stocking.

Thus, using current data on the growing stock volume for each stand, the above-ground live biomass of each stand was calculated by multiplying the growing stock volume by the corresponding conversion coefficients (Shvidenko et al. 2007).

To verify the results of the live biomass assessment using the model approach, the above-ground live biomass of trees and stands was evaluated on the SPs. This evaluation included measuring the height and diameter at breast height (DBH) of all trees at 1.3 m, as well as using normative reference tables to estimate the live biomass of growing tree crowns (Lakyda et al. 2013). The total above-ground live biomass of each tree was determined by summing the components of the tree's live biomass.

On all SPs, we measured tree DBH and height to construct height curves and calculate stem volume for each tree using Nikitin's equation (Bilous et al. 2021). Using the density of the tree components of above-ground live biomass of the main forest-forming species in Ukraine (Lakyda et al. 2011; Fischer et al. 2026) and stem volume data, we obtained live biomass parameters for stems. According to the models presented in the handbook, we calculated the biomass of bark, small branches, and leaves, considering the parameters of each tree. The sum of above-ground live biomass fractions allowed us to establish the total live biomass of each tree and the stand as a whole.

Each SP (Tab. 1) was characterised at the time of its establishment mainly by typical, native, broad-leaved tree species, apart from *Robinia pseudoacacia* (ROPS). The composition of trees on each SP was as follows:

SP1: *Acer platanoides* (ACPL) – 142 trees, *Quercus robur* (QURO) – 98 trees, *Robinia pseudoacacia* (ROPS) – 5 trees, *Tilia cordata* (TICO) – 1 tree, *Ulmus laevis* (ULLE) – 2 trees, and 12 snags of ACPL and QURO.

SP2: ACPL – 36 trees, *Carpinus betulus* (CABE) – 215 trees, QURO – 33 trees, TICO – 23 trees, and 7 snags of CABE and QURO.

SP3: ACPL – 8 trees, CABE – 181 trees, QURO – 7 trees, ROPS – 1 tree, TICO– 6 trees, ULLE – 10 trees, and 1 dried CABE.

SP4: ACPL – 73 trees, CABE – 57 trees, QURO – 63 trees, TICO – 9 trees, ULLE – 1 tree, *Fraxinus excelsior* (FREX) – 1 tree, and 22 snags of ACPL, CABE, QURO, and TICO.

The largest number of trees on the four SPs was represented by ACPL, CABE, and QURO. The density of tree stands on the sample plots was as follows: SP1 – 510 trees per hectare, SP2 – 357 trees per hectare, SP3 – 486 trees per hectare, and SP4 – 779 trees per hectare.

Paired comparisons between the model-based approach and above-ground biomass estimates on permanent sample plots were conducted using the Wilcoxon signed-rank test (Hollander et al. 2014). Analyses were performed separately for the 2016/2017 and 2023 datasets due to the small number of sample plots. The magnitude of between-method differences was described using the median of paired differences.

The assessment of carbon storage in the above-ground live biomass was conducted using data on the carbon content in absolutely dry wood and bark (50%) and leaves (45%) (Matthews 1993).

The amount of oxygen produced during forest growth was estimated based on the stoichiometric relationship of oxygenic photosynthesis, assuming that the accumulation of 1 t of biogenic carbon corresponds to the release of 2.67 t of molecular oxygen. This conversion is derived from the molar balance of CO_2 fixation and O_2 evolution during photosynthesis and is widely applied in forest ecosystem-level productivity and gas-exchange studies (Stirbet et al. 2020). To quantify the energy accumulated in forest stand biomass, the value of 35.78 GJ t C^{-1} was applied as the energy equivalent of carbon, corresponding to the higher heating value of elemental carbon under complete oxidation to CO_2 and representing a fundamental thermochemical constant (Reichle et al. 1973).

RESULTS AND DISCUSSION

The structure of stands in the experimental SPs of the park showed notable changes in tree status from 2016 to 2023 (Tab. 2). Across all plots, the number of dead trees increased, ranging from 1 to 30 trees. In the SP1, the percentage of dead trees rose from 4.6% in 2016 to 14.9% in 2023, with ROPS, ULLE, and TICO trees maintaining stable vitality. SP2 was dominated by CABE trees, with a decrease in live trees from 215 in 2016 to 201 in 2023 and an increase in dead CABE trees to 15, representing 4.7% of the total. Dead QURO and ACPL trees also showed an increase, reaching 4.7% and 0.6%, respectively, in 2023.

Table 1. Description of studied forest stands (Schepaschenko et al. 2019)

Sample plot	Year of SP establishment	Coordinates	Age, years	Site index	Area, ha	Number of trees
1	2016	50.335422N 30.481637E	~80	I	0.51	260
2		50.343174N 30.484455E	~180	I	0.88	314
3	2017	50.343387N 30.492641E	~180	I^a	0.44	214
4		50.343335N 30.497189E	~80	I	0.29	226

The SP3 recorded the highest number of snags, with 11.3% of CABE, 0.5% of ACPL, and 0.5% of TICO trees being dead. SP4 reported an increase in the percentage of dead CABE and QURO trees to 7.3% and 7.7% of the total trees, respectively, in 2023, with dead TICO and ACPL trees accounting for 4.1% and 3.2%, respectively.

The full tree inventory on the SPs, aimed at measuring key urban forest stand parameters from 2016 (2017) (Bilous et al. 2017) to 2023, also included estimations of live and dead biomass (Tab. 3). On the SP1, above-

Table 2. Distribution of trees by vitality status on SPs, 2016–2023

Sample plots	Tree status	CABE	ACPL	QURO	TICO	ULLE	ROPS	FREX
2016 (Schepaschenko et al. 2019)								
1	Alive	-	142	98	1	2	5	-
	Snag	-	6	6	-	-	-	-
2	Alive	215	36	33	23	-	-	-
	Snag	2	-	5	-	-	-	-
2017 (Schepaschenko et al. 2019)								
3	Alive	181	8	7	6	10	1	-
	Snag	1	-	-	-	-	-	-
4	Alive	57	73	63	9	1	-	1
	Snag	8	2	8	4	-	-	-
2023								
1	Alive	-	134	69	1	2	5	-
	Snag	-	7	30	-	-	-	-
	Missing	-	7	5	-	-	-	-
2	Alive	201	34	23	23	-	-	-
	Snag	15	2	15	-	-	-	-
	Missing	1	-	-	-	-	-	-
3	Alive	157	7	7	5	10	1	-
	Snag	24	1	-	1	-	-	-
	Missing	1	-	-	-	-	-	-
4	Alive	44	67	54	4	1	-	1
	Snag	16	7	17	9	-	-	-
	Missing	5	1	-	-	-	-	-

Table 3. Indicators of above-ground live biomass of SPs, 2016–2023

Sample plots	Year	Above-ground live biomass, t·ha^{-1}					Snags, t·ha^{-1}	Total biomass of the stand, t·ha^{-1}
		stem	coarse branches	small branches	leaves	total biomass		
1	2016	201	22	70	17	**310**	3	**313**
	2019	201	23	66	16	306	15	321
	2020	196	22	62	15	295	21	316
	2021	191	22	60	15	288	25	313
	2023	199	23	61	15	**298**	21	**319**
2	2016	286	42	59	14	**401**	8	**409**
	2019	287	42	57	14	**399**	18	**417**
	2020	287	42	57	14	399	18	417
	2021	294	43	58	14	410	20	430
	2023	233	33	38	9	**312**	65	**377**
3	2017	220	39	35	8	**303**	0 (0.1)	**303**
	2019	233	42	35	8	318	2	320
	2020	233	41	35	8	318	3	321
	2021	239	43	37	9	328	0 (0.3)	328
	2023	240	43	37	9	**329**	6	**335**
4	2017	160	20	72	18	**270**	10	**280**
	2019	168	22	73	18	281	11	292
	2020	162	21	70	17	271	20	291
	2021	165	22	69	17	273	19	292
	2023	167	22	69	17	**275**	24	**299**

ground live biomass decreased by 12 t·ha^{-1} from 2016 to 2023, with QURO trees contributing the largest share at 67% in 2023 (Fig. 1). A 22.2% decrease in above-ground live biomass was observed on the SP2, largely due to an increase in dead and wind-blown QURO trees. QURO trees contributed the majority of live biomass dry matter. On the SP3, above-ground live biomass increased by 26 t·ha^{-1}, driven by CABE and QURO trees, with CABE increasing by 11 t·ha^{-1}, QURO by 13 t·ha^{-1}, and ULLE by 4 t·ha^{-1}. The SP4 experienced a 5 t·ha^{-1} increase in above-ground live biomass, predominantly comprised of QURO trees, which made up 81% of the total live biomass.

During natural competition for space and the subsequent mortality of weakened trees, a significant surge in snag accumulation was observed on SPs (Fig. 2).

To verify the accuracy of the live biomass assessment

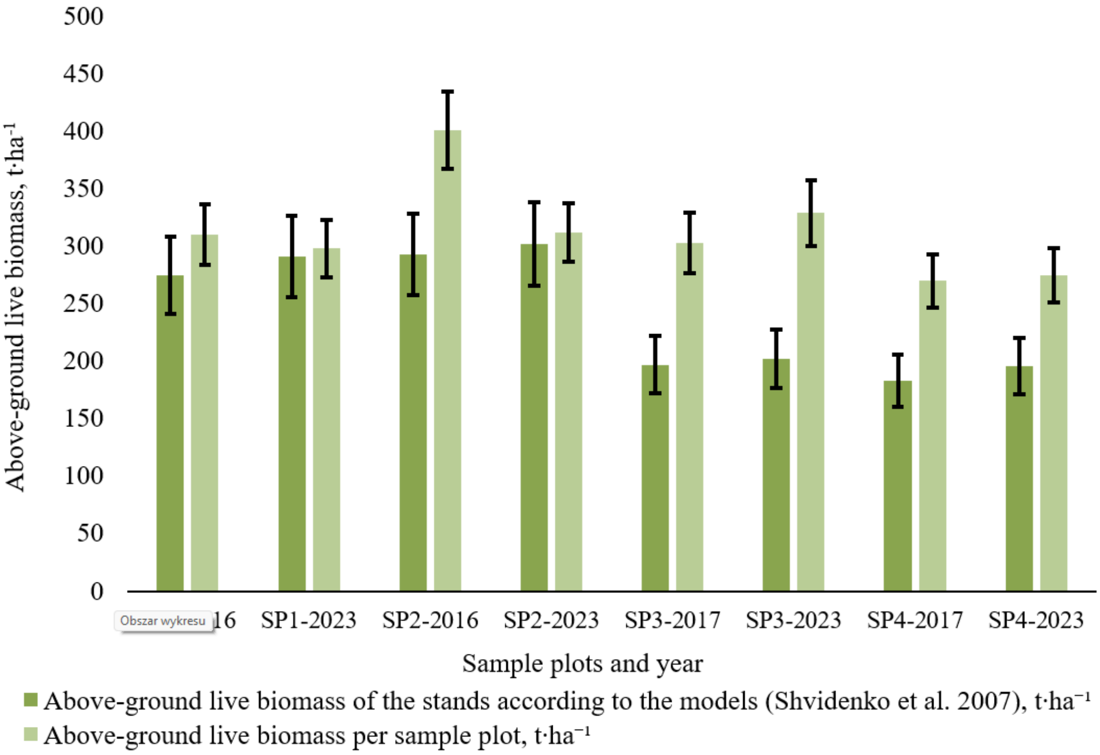

Figure 1. Above-ground live biomass on the SPs, 2016–2023

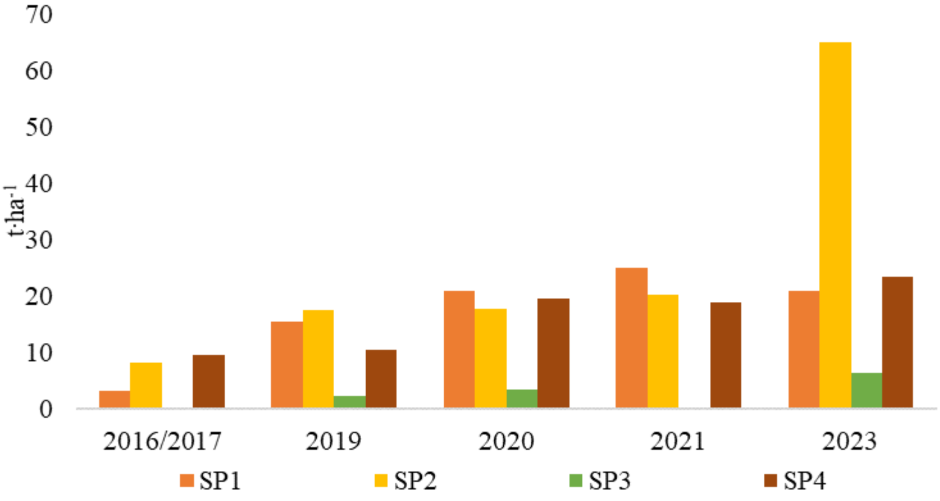

Figure 2. Snags on the SPs

using a model approach, the above-ground live biomass of tree stands in an absolutely dry state was assessed for each tree stand within inventory sections where SPs were established (Shvidenko et al. 2007).

The live biomass assessment results for the studied urban forests were analysed using two approaches (Tab. 4). The first approach involved estimating live biomass with a mathematical equation adapted for the European part of Eurasia, based on the models (Shvidenko et al. 2007). The second approach used data from SPs.

According to the models developed by Shvidenko et al. (2007), all four SPs in the forest stands showed increases in aboveground live biomass during the study period. However, on SP1 and SP2, the actual live biomass decreased during this period (Fig. 3). The relative deviation of the growing stock volume, according to the model, compared to the SP data ranged from -37% to 17%. The average relative deviation in growing stock volume across all accounting years (2016, 2017, and 2023) was -9%, suggesting a possible systematic underestimation of stem volume data during forest inventory.

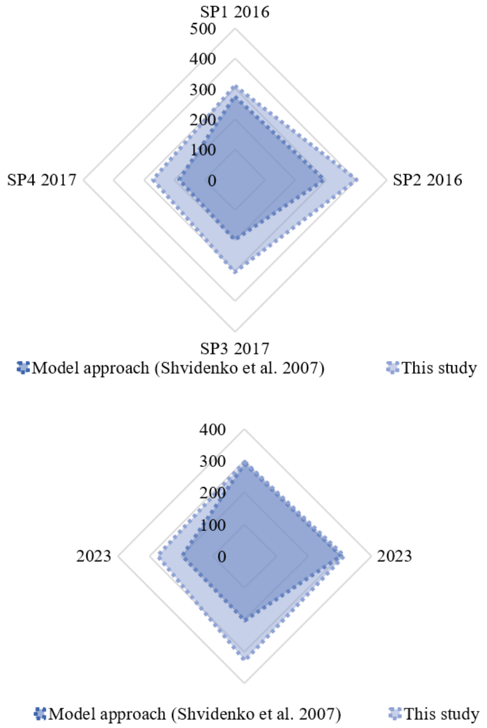

Figure 3. Comparison of parameters of the SP's total live biomass

The relative deviation of above-ground live biomass, based on the model approach compared to the SPs data, ranged from -39% to -2%, with an average of -22% across all accounting data from 2016 (2017) to 2023. This greater deviation in above-ground live biomass compared to the growing stock volume (over bark) is likely due to the significant influence of crown live biomass on the variability of above-ground live biomass, as well as the difference in growing stock volume derived from forest management planning data and from measurements conducted on permanent sample plots (Tab. 4). Across both observation periods, the approach for above-ground biomass on SPs values consistently yielded higher values than the corresponding model-based estimates for all sample plots, resulting in uniformly positive paired differences. The median difference reached 96.5 $t \cdot ha^{-1}$ in 2016/2017 and decreased to 44.5 $t \cdot ha^{-1}$ in 2023, suggesting a persistent positive bias of the SPs data relative to the models. Although the Wilcoxon signed-rank test (Hollander et al. 2014) did not indicate statistical significance ($p = 0.125$ for both periods), the large effect size ($r=0.77$) points to a strong and coherent between-method difference, with the non-significant result mainly reflecting the limited sample size.

Discrepancies between model-based and permanent sample plot estimates of above-ground live biomass were additionally evaluated using the mean absolute error

Table 4. Comparison of above-ground live biomass indicators of tree stands using different assessment approaches, 2016–2023

Sample plot	Year	Growing stock volume according to forest management planning, $m^3 \cdot ha^{-1}$	Growing stock volume of SP, $m^3 \cdot ha^{-1}$	Deviation, %	Above-ground live biomass of the stands according to the models (Shvidenko et al. 2007), $t \cdot ha^{-1}$	Above-ground live biomass of SP, $t \cdot ha^{-1}$	Deviation, %
1	2016	350	359	-3	275	310	-11
	2023	370	353	5	291	298	-2
2	2016	320	507	-37	293	401	-27
	2023	340	407	-16	302	312	-3
3	2017	290	378	-23	197	303	-35
	2023	300	412	-27	202	329	-39
4	2017	330	289	14	183	270	-32
	2023	350	299	17	196	275	-29

(MAE). During the initial observation period (2016/2017), MAE amounted to 84 t·ha-^{1}, reflecting considerable differences between the two estimation approaches. By 2023, MAE had decreased to 55.75 t·ha-^{1}, indicating a closer agreement between model-derived and field-based biomass estimates. The observed reduction in MAE may be attributed to a more accurate determination of growing stock volume obtained in this study using forest management planning methods, compared with standard production measurements applied during routine forest inventory. Variability in growing stock estimates constitutes a major source of uncertainty and directly influences differences in above-ground biomass values produced by the model-based approach.

The assessment and comparison with previous results of the EEI study of the total live biomass of the stands in the Feofania Park for the period 1958–2023 (Bilous et al. 2017), according to the model approach, revealed fluctuations in live biomass density (Tab. 5). Due to periodic changes in the park's area, the analysis focused on the density of above-ground live biomass (t·ha^{-1}) to understand the dynamics. A notable increase in live biomass density (by 57%) was observed from 1958 to 1979. However, by 1991, live biomass density had decreased by 25% compared to 1979. This decline continued alongside reductions in the park area until 2013. Since 2013, with the park's area stabilising at 107 hectares, live biomass density has increased, reaching 241 t·ha^{-1} (Fig. 4), indicating a trend towards sustainable management of urban forest stands in the park.

The structure of the accumulated total live biomass in various components showed a tendency to increase over the period from 1958 to 2023. The average percentage of stem biomass accounted for 60% of the total live biomass. Among other components, roots accounted for a significant share, comprising 21% of the total live biomass in urban forests. Branches contributed an average of 12%. The green forest floor, understory, and saplings contributed 2%, while leaves accounted for the smallest part of live biomass, less than 1%.

Table 5. The total live biomass of forest stands of the Feofania Park, 1958–2023

Year	Area, ha	Live biomass of the forest, thousands of tons							Total live biomass, thousands of tons	Live biomass density, t·ha^{-1}
		stem over bark	bark	branches	leaves	roots	green forest floor	understory and undergrowth		
1958	130.6	13.7	2.1	2.9	0.3	5.4	0.5	0.5	23.3	178
1979	144.7	24.8	3.7	5.1	0.4	9.0	0.6	0.6	40.5	280
1991	136.7	18.5	2.8	3.7	0.3	6.7	0.7	0.5	30.4	222
2000	135.7	19.3	2.8	3.8	0.3	6.5	0.7	0.8	31.4	231
2004	115.5	16.3	2.4	3.1	0.2	5.6	0.6	0.7	26.5	230
2013	107.0	12.5	1.8	2.3	0.2	4.3	0.6	0.6	20.5	191
2016	107.0	13.2	2.0	2.5	0.2	4.6	0.6	0.6	21.6	202
2021	107.0	14.4	2.1	2.7	0.2	4.7	0.6	0.6	23.0	215
2023	107.0	15.5	2.4	3.1	0.2	5.6	0.7	0.7	25.8	241

Source: developed by the authors, data up to 2013 (inclusive), adapted from the IEE sources (Bilous et al. 2017)

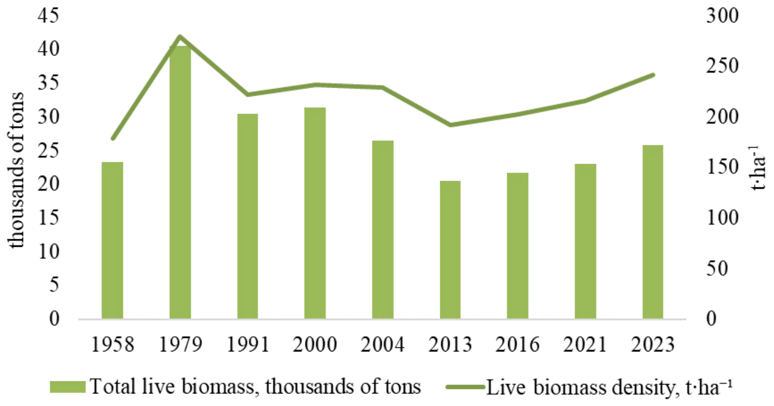

Figure 4. Live biomass of forest stands of the Feofania Park. Data up to 2013 adapted from the IEE sources (Bilous et al. 2017).

The carbon cycle in forest ecosystems is influenced by the productivity of urban forests, their diversity, and anthropogenic factors. In this context, nature reserve areas provide an important ecological service, particularly as carbon storage. In the floodplain forests of Kyiv, annual carbon sequestration in *Quercus robur* stems increases with tree age (Prokopuk 2018). Mature oak trees, aged 200 years or more, can sequester up to 20 kg of carbon per year in their stem wood (Prokopuk and Netsvetov 2016).

Based on data on the live biomass of stands, the amount of carbon storage was determined to be 13.0 GgC in 2013 (Fig. 5). The density of stored carbon in the total live biomass of forest stands increased by 27%, from 89 MgC·ha^{-1} in 1958 to 122 MgC·ha^{-1} (Tab. 6).

The highest rate of stem carbon storage was recorded in 1979, at 12.4 GgC (16.8%), while the lowest was recorded in 2013, at 6.3 GgC (8.6%). The reduction in forest area in the park significantly impacted overall carbon storage indicators during the studied period, with a decrease of 23.6 hectares from 1958 to 2013.

Ecosystems provide various services that depend on their species composition, spatial distribution, and other factors. Forest ecosystems, both globally and regionally, are among the primary producers of oxygen. Additionally, the oxygen production capacity of urban forests is a key metric in evaluating ecosystem services, alongside carbon storage and temperature regulation. These functions are essential for enhancing atmospheric air quality and align with the primary objectives of international and national environmental programs, as well as EU Directives ratified by Ukraine (Directive (EU) 2016/2284 2016). In general, the oxygen-producing capacity of urban forest stands of the Feofania Park depends on their

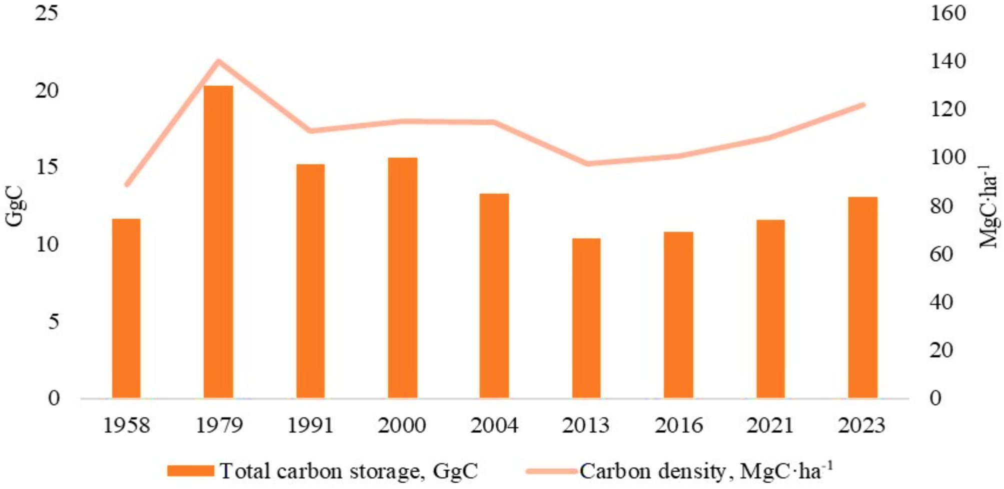

Figure 5. The carbon storage in the live biomass of forest stands in the Feofania Park, 1958–2023.Data up to 2013 adapted from the IEE sources (Bilous et al. 2017).

Table 6. The carbon storage in live biomass components. Data up to 2013 adapted from the IEE sources (Bilous et al. 2017).

Year	Area, ha	Carbon storage in live biomass components, GgC							Total carbon storage, GgC	Carbon density, MgC·ha^{-1}
		stem over bark	bark	branches	leaves	roots	green forest floor	understory and undergrowth		
1958	130.6	6.8	1.0	1.4	0.1	2.7	0.2	0.2	11.6	89
1979	144.7	12.4	1.9	2.5	0.2	4.5	0.3	0.3	20.2	140
1991	136.7	9.2	1.4	1.8	0.1	3.4	0.3	0.3	15.1	111
2000	135.7	9.6	1.4	1.9	0.1	3.2	0.3	0.4	15.6	115
2004	115.5	8.2	1.2	1.6	0.1	2.8	0.3	0.3	13.2	115
2013	107.0	6.3	0.9	1.2	0.1	2.1	0.3	0.3	10.2	95
2016	107.0	6.6	1.0	1.3	0.1	2.3	0.3	0.3	10.8	101
2021	107.0	7.2	1.1	1.4	0.1	2.3	0.3	0.3	11.6	108
2023	107.0	7.8	1.2	1.6	0.1	2.8	0.4	0.4	13.0	122

area and the dynamics of net primary products (Fig. 6).

The temporal changes in average oxygen production show an increasing trend in recent years, rising from 254 Mg $O_2 \cdot ha^{-1}$ in 2013 to 288 Mg $O_2 \cdot ha^{-1}$ in 2023. Data on the total available live biomass of forests also allow for the estimation of the total amount of oxygen produced during the growth and development of living trees. In 2013, the total amount of oxygen produced was 27 Gg O_2, which increased to 31 Gg O_2 by 2023. This increase highlights the growing importance of forests in providing essential ecosystem services.

Forest phytocenoses are characterised by long-term carbon storage and gradual carbon emissions, accompanied by energy accumulation and transformation. These processes of substance transformation and circulation reflect the complex relationships within the ecosystem and occur alongside the development of forests' energy potential. A positive energy potential in these ecosystems indicates their sustainable development.

Indicators of the energy potential of the park's forests are derived from storage carbon dynamics. Like carbon dynamics, this indicator also depends on the park's area, which has changed and decreased over the past 65 years. The reduction in the park's area has influenced the varied dynamics of average energy stored in forest biomass, with the highest values recorded in 1979 at 5.0 TJ·ha^{-1} and the lowest in 1958 at 3.2 TJ·ha^{-1} (Fig. 7).

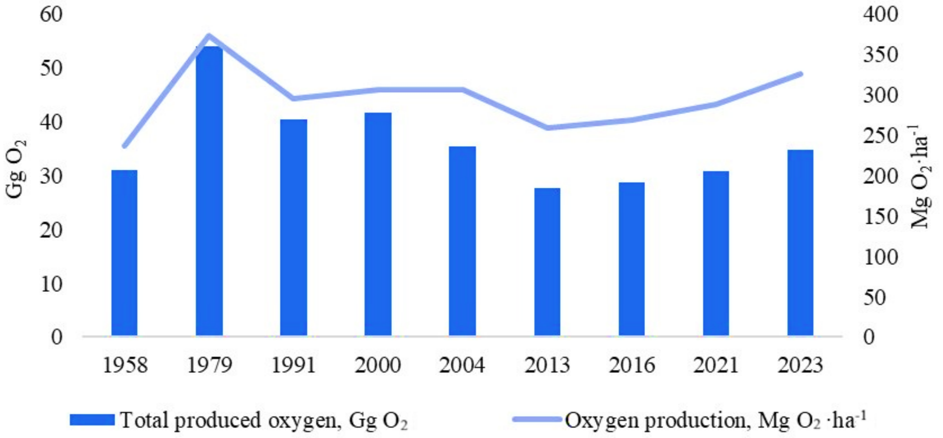

Figure 6. Oxygen production of forest stands in the Feofania Park, 1958–2023. Data up to 2013 adapted from the IEE sources (Bilous et al. 2017).

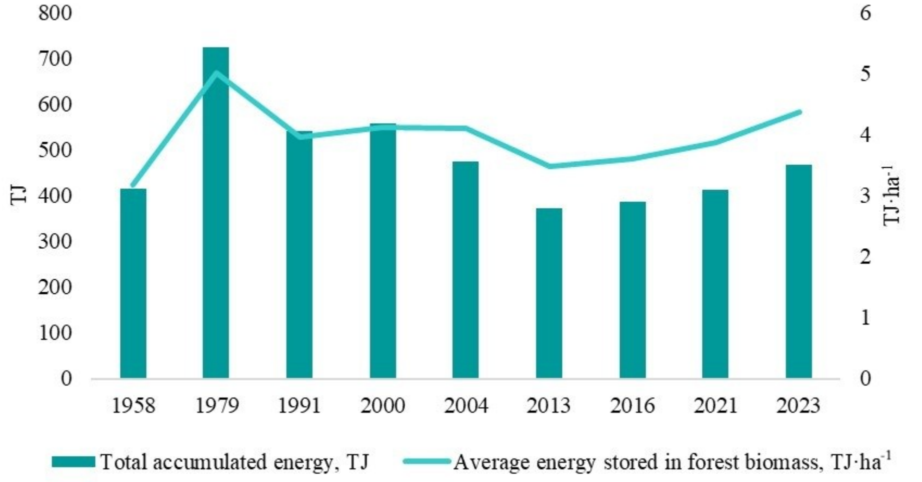

Figure 7. Energy stored in forest biomass in the Feofania Park, 1958–2023 Data up to 2013 adapted from the IEE sources (Bilous et al. 2017).

In recent years, there has been a clear trend of increasing energy potential in the forests, indicating stable development and the establishment of robust energy dynamics within the forest ecosystem. By 2023, the average energy stored in forest biomass had reached 4.4 $TJ \cdot ha^{-1}$. Given the park's conservation status, this stable energy potential is essential for preserving biodiversity across various ecosystem levels and ensuring the continued functionality of the urban forest stands.

CONCLUSIONS

This research provides validation of a biomass-based modelling approach at the forest-stand level using long-term observations from permanent sample plots established in the urban forests of Feofania Park. The comparison of model-based estimates with field measurements indicates that applying generalised biomass models to individual urban forest stands is associated with considerable uncertainty. This effect is most pronounced in structurally complex and uneven-aged stands with an increased share of dead trees, where tree mortality and crown biomass substantially influence overall above-ground biomass dynamics.

At the same time, the results show that the consistency of model-based biomass estimates increases when data are analysed for a set of forest stands rather than at the plot level. This pattern suggests that deviations are primarily driven by differences in the assessment of growing stock volume during forest management planning and by the structural heterogeneity typical of urban and protected forests, rather than by deficiencies in the model approach itself. Consequently, the accuracy of growing stock volume assessment remains a key prerequisite for the reliable application of biomass-based models in forest ecosystems.

The analysis also confirms the role of stand age and structural characteristics in shaping biomass dynamics and ecosystem service provision. Younger stands are characterised by higher relative biomass increment, whereas older, mixed and structurally complex stands dominated by mature oak trees store the largest proportion of carbon. These results emphasise the functional importance of structurally diverse urban forests for the long-term maintenance of ecosystem functions.

In summary, biomass-based models may be suitable for large-scale assessments of forest biomass and ecosystem services in urban and protected forests, provided that their limitations at the stand level are explicitly recognised. The combined use of model-based estimates and permanent sample plot data represents an effective approach for urban and protected forest monitoring and for supporting forest management decisions aimed at sustainable development.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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