ORIGINAL ARTICLE

Dynamics of surface fuel accumulation in Scots pine (*Pinus sylvestris* L.) forests of green zones of the cities of Kyiv and Kharkiv

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ABSTRACT

The aim of this study was to investigate the dynamics of forest fuel accumulation in relation to fire hazard in the green zones forests of Kyiv and Kharkiv cities. The research employed analytical–calculative, monitoring and generalising methods to assess the formation and accumulation of forest fuels and to provide practical recommendations.

The results identified key factors influencing the accumulation of surface forest fuels within these urban forests. In Kyiv's green zone, pine stands growing under the most widespread forest site conditions (B_{2-3}: fresh and moist subor types), the total litter load (in absolutely dry condition) ranged from 8.1 to 46.0 t/ha, with litter layer thickness varying between 2.1 and 8.1 cm. In Kharkiv's green zone forests, significantly higher fuel loads were recorded, ranging from 15.6 t/ha in young pine stands to 60.0 t/ha in mature and overmature forests.

A litter stock modelling approach was applied to estimate the accumulation of forest litter and duff in the peri-urban forests of Kyiv and Kharkiv using the conversion coefficients (R_v) derived from empirical stand parameters (DBH, density and age). The models demonstrated high accuracy ($R^2 = 0.75-0.98$) and confirmed that the highest surface fuel accumulation in pine stands occurs at 60–75 years.

It was confirmed that pine stands in Kharkiv's green zones growing under fresh subor conditions accumulate 22.8% more surface fuels. The difference in normalised mean values was statistically significant ($t_{st} = -1.89$, $t_{crit} = 1.69$; $p = 0.03$).

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Introduction

Over the past decade, approximately 274,500 ha of Scots pine (*Pinus sylvestris* L.) stands in Ukraine have been damaged by industrial emissions, human-induced activities, pest outbreaks, wildfires and forest diseases. In the forest enterprises of Central Polissya, there has been a persistent trend of significant losses in commercial pine timber due to large-scale forest fires (Sydorenko and Sydorenko 2023). The wildfires of 2016, 2018 and particularly 2020 were especially devastating for Ukraine's forestry sector. The 2020 fires, which affected Rivne, Kyiv, Zhytomyr and Chernihiv regions, destroyed up to 72% of the forest raw material base and protected natural areas, led to the burning of peatlands and triggered a decline in groundwater levels. This, in turn, resulted in reduced productivity of pine stands and weakened their sanitary-hygienic, protective, recreational, water-conserving and other ecological functions.

Due to global climate change, wildfire danger in Ukrainian forests has nearly doubled over the past 40 years (San-Miguel-Ayanz et al. 2023; San-Miguel-Ayanz et al. 2024). More than 90% of forest fires in Ukraine are caused by human activity (Sydorenko et al. 2021; Levchenko et al. 2024). The frequency and number of fires increase in areas with high population density, particularly in the greenbelt forests of major cities, where socio-economic factors exacerbate the problem of fire occurrence and spread. Damage or destruction of forest stands by fire leads to weakening of their ecological and social functions, thereby posing a threat to the environmental safety of large urban centres (Levchenko et al. 2023; Levchenko et al. 2018; Levchenko et al. 2024).

The highest number of wildfires in the green zones of Kyiv and Kharkiv is typically recorded in May (Yavorovskyi and Hurzhii 2017). The period of greatest fire danger spans from April to September, with fire frequency peaking in June and July. Both the frequency and severity of wildfires increase sharply during drought years and months (Levchenko et al. 2018). A clear relationship has been established between fire occurrence and the presence of people or groups in forested areas. The time of highest fire risk is from 12:00 to 16:00 on weekends and the days preceding them. Fires in greenbelt forests predominantly occur in compartments adjacent to roads or settlement boundaries (Sydorenko et al. 2021; Levchenko et al. 2018; Levchenko et al. 2024).

Since the beginning of the large-scale invasion, this problem has become considerably more acute (Voron et al. 2018; Sydorenko and Sydorenko 2017; Sydorenko et al. 2023). In 2024, over 40% of the total area burned by landscape fires in Europe, North Africa and the Middle East occurred in Ukraine (San-Miguel-Ayanz et al. 2025). Given that the most intense hostilities took place near Kharkiv and Kyiv, the green zone forests of these two cities are heavily contaminated with unexploded ordnance (UXO), and large areas are mined. Consequently, the implementation of fire prevention and suppression measures in these forests is significantly constrained.

In Ukraine, wildfire hazard assessment predominantly relies on the characteristics of forest fuel complexes, based on proxy indicators such as forest stand parameters and site type (soil richness and moisture). Fire behaviour modelling depends on quantitative and qualitative data on forest fuels, terrain and climatic conditions (Finney et al. 2023). However, fire ecology research focused on fuel assessment and modelling in Ukraine remains limited, varying across site types and methodologies. Studying the dynamics of surface forest fuel formation will provide a more comprehensive basis for assessing fire hazard and wildfire risks. This knowledge is essential for prioritising fuel management interventions and reducing wildfire risk in the most vulnerable green zone forests. In this context, quantifying litter accumulation – the principal surface fuel in pure pine stands – becomes a critical task for contemporary pyroecological research.

Material and methods

To study the accumulation of forest litter and duff, we established a series of temporary sample plots (TSPs) in typical pine (*Pinus sylvestris* L.) stands within the green zones of Kyiv and Kharkiv, representing both fresh and moist soil conditions. The research focused primarily on assessing surface fuels, specifically forest litter and duff.

TSPs were established following the national standard 'SOU 02.02-37-476:2006 – Trial Forest Management Areas. TSPs. On each sample plot, five transects were laid out for assessing fine and coarse woody debris in accordance with the Fire Effects Monitoring

and Inventory System (FIREMON) protocol (Lutes et al. 2006).

All forest sites were classified according to soil moisture and fertility using the system developed by Pogrebnyak (1955). Moisture classes ranged from 0 (very dry) to 5 (very wet), and fertility classes from A (poor) to D (rich), with site types expressed as combinations (e.g. A_2, B_3).

To estimate the forest floor fuel load, 1 m² subplots were established in each stand. Sampling was conducted during July–August, after litter formation and before needle fall. In this study, litter was assumed to consist of two distinct layers: a fresh litter layer and a semi-decomposed duff layer. Sampling followed the method described by Rodin and Bazilevich (1965). Each layer was collected and weighed separately in the field. Before collection, the thickness of each layer was measured. Herbaceous vegetation, shrubs, regeneration and undergrowth were removed. Litter, leaves, mosses and lichens within the plot boundaries were carefully collected and placed into plastic bags. The fresh mass was recorded in the field, after which samples were dried for 24 h at 100–105°C to determine the absolutely dry weight.

Modelling of litter stocks was performed by calculating conversion rate models (Rv) based on actual data such as modelling of the standing phytomass (Avramchuk and Bilous 2015; Sydorenko 2019).

$$Rv = M_{mp}/M \qquad (1)$$

where:
M_{mp} – denotes the mortmass of forest litter in t × ha^{-1},
M – denotes the trunks stock in the bark of a stand in m³ × ha^{-1}.

The following equation was used for modelling (Avramchuk and Bilous 2015). For this purpose, non-linear multiple regression analysis was used:

$$Rv = a_0 \times x^{a1} \times x_n^{an} \qquad (2)$$

where:
Rv – a dependent variable (conversion rate for litter load),
$a_0 \dots a_n$ – regression coefficients,
$x \dots x_n$ – independent variables.

The average mass of forest litter from all sample plots was extrapolated to a per-hectare basis. The collected data were processed using methods of mathematical statistics. Statistical analysis was performed using Microsoft Office Excel and Statistica 10 software.

Results

It was found that the forest litter load under the most common site conditions (B_{2-3}), which dominate in the pine forests of both Kyiv and Kharkiv, ranged from 8.1 to 46.0 t/ha (absolutely dry weight) in the peri-urban forests of Kyiv, with the litter layer depth varying between 2.1 and 8.1 cm (Tab. 1). In contrast, substantially higher litter loads were observed in the green zone forests of Kharkiv, ranging from 15.6 t/ha in young pine stands to 60.0 t/ha in mature and overmature *Pinus sylvestris* stands (Fig. 1). The study revealed that litter accumulation increases with stand age ($r = 0.65$, $p = 0.05$) and is also positively correlated with key mensurational characteristics such as mean tree height ($r = 0.77$) and diameter ($r = 0.61$, $p = 0.05$).

A decrease in stand density was associated with a reduction in forest litter mass, demonstrating a negative correlation ($r = -0.49$, $p = 0.05$). The strongest correlation between litter accumulation and stand characteristics in *Pinus sylvestris* forests was observed between the absolutely dry litter mass per hectare and total stand volume. In the peri-urban forests of Kharkiv, this correlation coefficient reached $r = 0.90$ ($p = 0.05$), while in Kyiv forests it was $r = 0.73$.

It was found that the highest accumulation of forest fuels in the green zones of Kyiv in Scots pine (*Pinus sylvestris* L.) stands is typical at the pre-mature age of 75 years. At this stage, biological litterfall results in the formation of a substantial forest fuel layer, reaching an average depth of 8.1 ± 0.3 cm. This creates a high fire hazard, and such fuel loads, under conditions of elevated fire danger, may lead to intensive litter combustion and even intensive mortality of trees in the stand.

A similar pattern was observed in the peri-urban forests of Kharkiv (Tab. 2). The maximum forest fuel accumulation was recorded in *Pinus sylvestris* stands aged between 60 and 80 years. Notably, these age class-
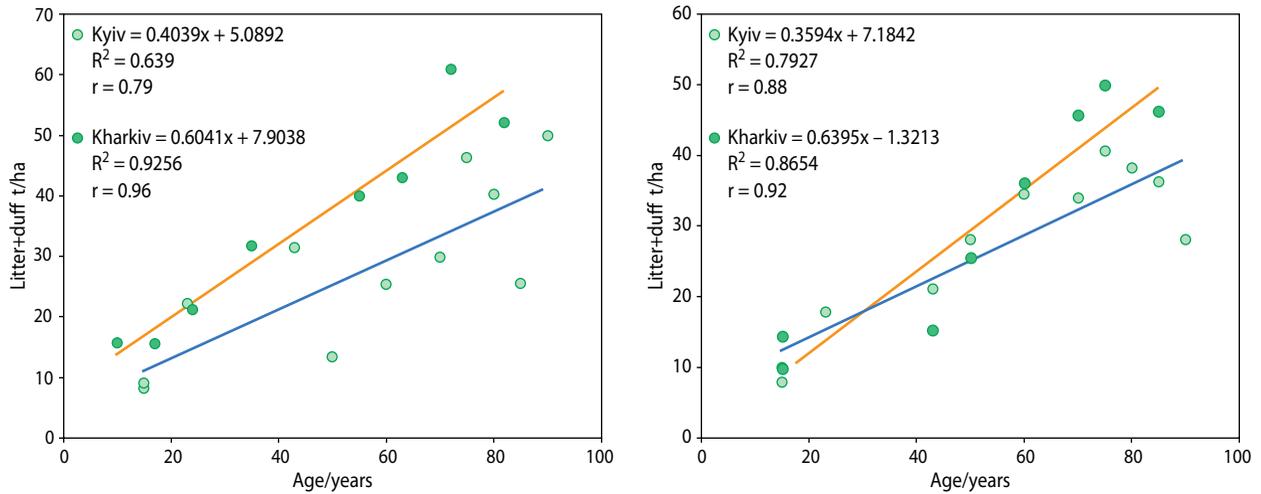
Figure 1. Dynamics of forest litter load in the peri-urban forests of Kyiv and Kharkiv based on field (empirical) data from sample plots (left) and modelled estimates (right), averaged for the period 2021–2023

Table 1. Characteristics of forest fuel loads in the green zones of Kyiv dominated by Scots pine (*Pinus sylvestris* L.) (mean values for 2021–2023)

Age, years	DBH, cm	Heigh, m	Relative density	Stock, $m^3 \times ha^{-1}$	Load (litter + duff), t	Depth (litter + duff), cm
15	6.2	7.9	0.89	54	9.0	2.38
15	5.9	7.4	0.88	43	8.1	2.10
23	12.6	10.4	0.92	99	22.1	2.70
43	15.1	16.3	0.74	173	31.4	5.20
50	23.4	20.9	0.67	274	13.4	2.80
60	25.7	24.1	0.72	314	25.3	5.70
70	27.6	23.4	0.80	273	29.8	6.10
75	32.3	25.4	0.74	370	46.3	8.10
80	31.5	26.0	0.83	299	40.2	6.20
85	32.4	26.7	0.79	306	25.4	5.30
90	34.2	27.1	0.65	313	49.8	8.60
LSD $_{0.05}$	1.24	1.28	1.23	1.34	1.38	1.42

LSD - The smallest significant difference.

es in the site conditions of Kharkiv's green zones are particularly vulnerable to ignition and fire spread due to careless or negligent human activity during recreational activities.

To estimate the thickness and accumulation of forest fuel litter and duff in the peri-urban recreational zones of Kyiv and Kharkiv, a litter stock modelling approach was applied. The model was based on the calculation of conversion coefficients (*Rv*) using empirical data, following the approach typically used for forest biomass modelling (Hurzhii 2017). The most effective predictor variables identified for inclusion in the models were: d – mean tree diameter DBH (cm), P – relative stand density and A – stand age (years).

Accordingly, the model developed to estimate the conversion coefficient (R_v) for total forest litter mortmass in the peri-urban recreational forests of Kharkiv is expressed as:

Table 2. Characteristics of forest fuel loads in the peri-urban green zones of Kharkiv dominated by Scots pine (*Pinus sylvestris* L.) (mean values for 2021–2023)

Age, years	DBH, cm	Heigh, m	Relative density	Stock, m³ × ha⁻¹	Load (litter + duff), t	Depth (litter + duff), cm
10	10	4.3	0.85	12	15.61	1.4
17	8	7.6	1.00	26	15.54	1.6
24	14	10.0	0.75	115	21.09	2.1
35	16	13.2	0.8	144	31.73	1.4
55	28	16.0	0.75	217	39.87	3.6
63	24	17.8	0.79	270	42.87	4.3
72	28	24.2	0.80	433	60.83	5.4
82	29	22.6	0.75	389	51.96	4.8
124	46	26.0	0.40	243	33.1	6.4
LSD $_{0.05}$	1.34	1.26	1.32	1.43	1.25	1.16

LSD - The smallest significant difference.

Table 3. Comparison of modelled surface fuel load in the peri-urban recreational forests of Kyiv and Kharkiv (mean values for 2021–2023)

Age, years	D, cm	H, m	P	M, m³ × ha⁻¹	R_v modelled		Litter + duff load, ton	
					Kyiv	Kharkiv	Kyiv	Kharkiv
15	6.2	7.9	0.89	54	0.188	0.264	10.1	14.299
15	5.9	7.4	0.88	43	0.185	0.229	7.975	9.8854
23	12.6	10.4	0.92	99	0.18	0.529	17.882	52.348
43	15.1	16.3	0.74	173	0.122	0.09	21.12	15.526
50	23.4	20.9	0.67	274	0.102	0.093	28.036	25.499
60	25.7	24.1	0.72	314	0.109	0.115	34.539	36.015
70	27.6	23.4	0.8	273	0.125	0.167	33.971	45.688
75	32.3	25.4	0.74	370	0.109	0.135	40.668	49.898
80	31.5	26	0.83	299	0.127	0.202	38.268	60.357
85	32.4	26.7	0.79	306	0.119	0.151	36.234	46.224
90	34.2	27.1	0.65	313	0.089	0.058	27.987	18.425
LSD $_{0.05}$	1.24	1.26	1.32	1.47	1.36	1.4	1.21	1.152

LSD - The smallest significant difference;

$$R_{v\text{ total}} = 1.71 \times d^{1.75} \times P^{4.83} \times A^{-1.66}$$
$$(R^2 = 0.98) \tag{3}$$

$$R_{v\text{ litter Kharkiv}} = 0.82 \times d^{2.47} \times P^{7.33} \times A^{-2.3}$$
$$(R^2 = 0.97) \tag{4}$$

$$R_{\text{duff Kharkiv}} = 1.016 \times d^{1.43} \times P^{3.84} \times A^{-1.39}$$
$$(R^2 = 0.97) \tag{5}$$

The model for determining the conversion coefficient (R_v) to estimate the forest litter and duff mortmass in the peri-urban forests of Kyiv is as follows:

$$R_{v\text{ total Kyiv}} = 0.34 \times d^{-0.043} \times P^{1.39} \times A^{-0.13}$$
$$(R^2 = 0.75) \tag{6}$$

The model for determining the conversion coefficient (R_v) to estimate the forest litter in the peri-urban forests of Kyiv is as follows:

$$R_{v \text{ litter Kyiv}} = 0.35 \times d^{-2.06} \times P^{-1.13} \times A^{-0.88} \quad (7)$$
$$(R^2 = 0.97)$$

When evaluating the modelled forest fuel stocks based on the developed models for the peri-urban green zone forests of Kyiv and Kharkiv, it can be stated that these methodological approaches to quantify and assess fuel accumulation are fairly objective (Tab. 3). In particular, they confirm the theoretical hypothesis that the most critical age for *Pinus sylvestris* in the peri-urban forests of Kyiv and Kharkiv ranges from 60 to 75 years. At this age range, the modelling results indicate the highest rates of litterfall and accumulation of surface forest fuels in Scots pine (*Pinus sylvestris* L.) stands. Given the variability in mensurational characteristics across the studied plots, it is advisable to compare the modelled fuel load data based on standardised stand parameters. This allows for a more accurate evaluation of trends in surface fuel accumulation.

In Scots pine plantations in the green zones of Kharkiv, growing on relatively poor sandy or sandy loam soils, fuel accumulation on the surface was 22.8 % higher compared to similar plantations in Kyiv. The difference in normalised mean values was found to be statistically significant ($t = -1.89$, $t_{crit} = 1.69$; $p = 0.03$).

Discussion

Our findings revealed that the increase in surface fuel loads with stand age is uneven, particularly in fresh subor site conditions within the peri-urban forests of Kyiv and Kharkiv. This pattern is attributed to the heterogeneity of mensurational characteristics in each stand (Yushchyk et al. 2022; Tkachuk 2003). Fuel accumulation tends to increase with stand development due to greater biomass input from the canopy (needle fall) and a slower decomposition rate. Notably, the study by Gurzhiy et al. (2021) reported that in fresh subor (B_2) conditions of Kyiv Polissya, the forest litter load increases with age, reaching a maximum in middle-aged stands (37.5 t/ha), and then declines in mature stands to 16.8 t/ha. These findings support our observation of uneven litter accumulation across stand age classes.

This process is especially pronounced in peri-urban recreational forests, where decomposition rates are significantly influenced by anthropogenic pressure on forest ecosystems (Monitoring and increasing… 2011). This is largely due to changes in soil chemistry – specifically, gradual acidification of soil solution caused by annual needlefall. The resulting acidic conditions reduce the activity of soil micro- and mesofauna (Hurzhii 2017; Levchenko et al. 2018). The fractional composition, thickness and amount of forest fuel are determined by multiple factors, among which stand characteristics (Sydorenko 2019) and soil moisture regime (hygrotop) play key roles. For example, studies conducted in Ukrainian Polissya (Rivne region) found that forest litter and duff accumulation ranged from 15.5 t/ha in 15-year-old stands to 140 t/ha in 139-year-old stands. Under fresh site conditions, litter load increased until the age of 80–90 years, after which it declined sharply, whereas under moist conditions, accumulation continued throughout the entire life cycle of the stand (Sydorenko et al. 2024).

Research by Soshenky and Humeniuk (2019) in Scots pine forests of Western Polissya, Ukraine, showed that litter load increases with stand age, reaching 99.5 t/ha in mature and overmature forests. This suggests that litter accumulation may be more intensive in Western Polissya than in central regions of Ukraine (Soshenskyi and Gumeniuk 2019).

As stand age and soil trophicity increase, so does the complexity of the fuel composition, and the total amount of fuel also increases (Sydorenko et al. 2024). Our analysis of litter and duff loads in Scots pine stands in the peri-urban forests of Kyiv and Kharkiv demonstrated that the accumulation is not uniform with age, especially under fresh subor and sugrud conditions. This inconsistency is explained by silvicultural differences between individual stands. The increase in needle biomass at specific age intervals results from enhanced crown development and reduced decomposition rates. Decomposition is further suppressed by acidification of the soil due to persistent needle fall. The highest needle biomass under fresh subor conditions was recorded at age 85 (5.93 t/ha), and the lowest was recorded at age 23 (2.39 t/ha). Under fresh sugroud conditions, the highest value was observed at age 30 (8.46 t/ha) and the lowest at age 80 (2.09 t/ha). In fresh bor conditions, needle biomass showed a more stable distribution, with a maxi-

mum of 3.70 t/ha at age 59 and a minimum of 1.62 t/ha at age 32.

Despite similar soil conditions, the peri-urban forests of Kyiv and Kharkiv are located in different natural zones with distinct climatic characteristics: Kyiv region experiences lower mean annual temperatures but slightly higher precipitation, while Kharkiv has warmer conditions with less rainfall. These differences may explain the higher mortmass accumulation in the more productive Scots pine stands under B_2 conditions in Kharkiv; however, this hypothesis requires further investigation.

Conclusions

1. Significant amount of surface forest fuels, particularly litter, accumulates in the green zone forests of Kyiv and Kharkiv, representing a key factor in wildfire hazard formation. The highest fuel loads were found in Scots pine stands aged 60–75 years.
2. Litter accumulation increases significantly with stand age, DBH, height and overall timber stock, while decreasing stand density is associated with reduced fuel loads.
3. In the green zone forests of Kharkiv, under fresh subor site conditions, surface fuel accumulation is 22.8% higher compared to Kyiv green belt forests. These differences are statistically significant.
4. The developed Rv coefficients reliably estimate dead fuel from stand parameters (age, diameter, density) and can be used to predict fuel load and fire hazard level in metropolitan urban forests.
5. Needle accumulation, as a component of surface fuel, is also most pronounced between the ages of 59 and 85. Its increase is associated with both higher stand biomass and slower decomposition of mortmass.
6. Assessing and modelling surface fuel loads enables the identification of high-risk wildfire zones, which is critically important for prioritisation of fuel management and protecting urbanised pine forests, especially under conditions of restricted access due to landmines and UXO contamination.

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