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Assessment of the surface forest fuel load in the Ukrainian Polissia

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Abstract

Background There is a clearly increasing trend of wildfires that become catastrophic in some countries such as the United States, Australia, Russia, Portugal, Greece, and Spain. Fuel is one of the key components that influences fire behavior and its effects. Assessing the fuel load and distribution of its components in the landscape provides effective fire management treatments in terms of fire prevention campaigns on a scientific basis. This study aims to evaluate the litter, duff, and herb fuels in highly flammable coniferous forest types in Ukrainian Polissia.

To estimate relationships between forestry variables that reflect the characteristics of the pine stand (DBH, height of the stand, age, relative density, stock of the plantation etc.) and the load of litter, duff, and herb fuels (CWD, FWD, litter, live grass, etc.), correlation analysis was used. To analyze difference between groups of sampling plots that have different forests, we use generalized linear mixed models including random effects of sampling plot type. Cluster analysis was performed using k-means partitioning method and Calinski-Harabasz criterion. To assess the significance of individual variables on which the variation of forest fuel depends, the random forest algorithm was used; for variable selection, we used two parameters: the percent increase in mean squared error and the Gini impurity index.

Results The research revealed that in the pine forest stands, the stock of litter and duff varies from 15.5 (15 years) to 140 ton/ha (139 years). When modeling, the humidity level of the forest site (soil) significantly affects the dynamics of forest fuel accumulation. In fresh types of forest-growing conditions, the forest litter stock increases to the age of 80–90 years; then, it strongly decreases, while in wet forest types, continuous forest fuel stock accumulation is established during the entire growth period. Moreover, the results showed that the forest fuel load was influenced by the soil fertility. The stock of live and dead herbaceous fuel in fresh and wet conditions is not statistically different, and soil moisture has not had a significant impact. Fine woody debris stocks were more dependent on stand productivity and practically does not depend on the soil fertility index, site moisture content, and its age and ranged from 0.4 to 1.9 t/ha (1 h), from 0.1 to 2.2 t/ha (10 h), and from 0 to 1.6 t/ha (100 h).

Conclusions The obtained results enabled to develop mathematical models for estimating litter and duff stocks in the Polissia forest stands based on stand characteristic and the soil humidity level. Moreover, the results will serve as basis to develop local forest fuel models as well as to determine potential fire hazards and a fire behavior modeling process in coniferous forests of that region. These models constitute the basis for the national set of fuel model development for each nature zone of Ukraine.

Keywords Forest fuel load, Fine woody debris, Fuel modeling, Forest litter, Forest duff, Wildfire hazard

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Resumen

Antecedentes Existe una tendencia creciente de incendios que se transforman en catastróficos en algunos países como los Estados Unidos, Australia, Rusia, Portugal, Grecia y España. El combustible vegetal es uno de los componentes clave que influencian el comportamiento del fuego y sus efectos. Determinar la carga y distribución de sus componentes en el paisaje provee de elementos para tratamientos efectivos de manejo en términos de campañas de prevención basadas en datos científicos. Este estudio busca evaluar los combustibles como la broza (i.e.litter), el mantillo (i.e. duff) y las hierbas en tipos de bosques de coníferas en Polesia, Ucrania. Para estimar las relaciones entre variables forestales que reflejen las características de un rodal de pinos (diámetro a la altura del pecho, altura del rodal, edad, densidad relativa, stock de la plantación, etc.), y la carga de broza, de mantillo (CWD, FWD, broza, pastos vivos, etc.), se usó análisis de correlación. Para analizar las diferencias entre los grupos de parcelas de muestreo que tenían diferente uso forestal, se usaron modelos mixtos generalizados incluyendo efectos del azar en cada tipo de parcela de muestreo. Se realizó un análisis de Clusters usando el método de particionamiento de las K-medias y el criterio de Calinski-Harabasz. Para determinar la significancia de las variables individuales sobre las cuales depende la variación de los combustibles forestales, se usó el algoritmo de bosque al azar (Random Forest algorithm), y para la selección de variables fueron usados dos parámetros: el porcentaje de incremento en el error cuadrático medio y el índice de impuridad de Gini.

Resultados La investigación reveló que en los rodales de pino el stock de broza y mantillo varió de 15,5 (en 15 años) a 140 ton/ha (139 años). Al realizar la modelación, el nivel de humedad del sitio forestal (suelo) afecta significativamente la dinámica de la acumulación de los combustibles. En condiciones de crecimiento del bosque con suelos más bien secos, el stock de broza se incrementa hasta una edad de 80–90 años, y luego disminuye drásticamente, mientras que, en sitios forestales húmedos, la acumulación continua de combustibles perdura por todo el período de crecimiento. Además, los resultados muestran que la carga de combustibles está influenciada por la fertilidad del suelo. El stock del combustible herbáceo vivo y muerto en condiciones de suelo secas o húmedas no fue estadísticamente diferente, y la humedad del suelo no tuvo un impacto significativo. Los restos de troncos finos fueron más dependientes de la productividad de los rodales sin depender prácticamente del índice de la fertilidad del suelo, de la humedad del sitio, o de su edad, oscilando en rangos entre 0,4–1,9 ton/ha (1 h); 0,1–2,2 ton/ha (10 h); 0–1,6 ton/ha (100 h).

Conclusiones Los resultados obtenidos permitieron desarrollar modelos matemáticos para estimar los stocks de broza y mantillo en rodales de los bosques de Polesia basados en las características de los rodales y el nivel de humedad del suelo. Además, los resultados servirán de base para desarrollar modelos de combustibles locales y también determinar el peligro potencial y el proceso de modelado del comportamiento del fuego en bosques de coníferas de la región. Estos modelos constituyen la base del conjunto nacional para el desarrollo de modelos de combustibles para cada zona natural de Ucrania.

Background

Megafires have been causing significant and sometimes irreparable damage to humanity during the last decades (Goldammer 2013, 2021; Pyne 2021). The New Age of Fire, characterized by large wildfires with increasing both duration and intensity, was defined by scientists as "Pyrocene" (Pyne 2021). There is a clearly increasing trend of wildfires which often become catastrophic in USA, Australia, Russia, Portugal, Greece, and Spain as well as in other countries (Goldammer 2013; Heyerdahl et al. 2014; Axelson et al. 2019; Roper 2020). Large wildfires destroy forests and other landscapes, settlements, and infrastructure, causing enormous social, environmental, and economic damage (FAO 2020; Goldammer 2013; Halleux 2020).

In Ukraine during 1992–2016, both the frequency of wildfires occurrence and burned forest area increased as well as in other countries e.g., in 1992 in Chernobyl Exclusion Zone; in 1996 in Kyiv, Chernihiv, Donetsk, and Luhansk oblasts (Zibtsev et al. 2019); in 2007 in Kherson oblast (9000 ha) and in Crimea (1000 ha) (Zibtsev 2007); in Chernobyl Exclusion Zone in 2015 (15,000 ha) (Evangeliou et al. 2016).

In 2020, unprecedented large forest and landscape fires occurred in Ukraine (Soshenskyi et al. 2021b): in Chernobyl Exclusion Zone (67,000 ha), Zhytomyr oblast (43,000 ha), Luhansk oblast (38,000 ha), and Kharkiv oblast (8000 ha) (Gumeniuk et al. 2021). The main driver of fires in 2020 was associated with critical weather conditions. These were characterized by prolonged droughts and high wind speed drying vegetation fuels (Soshenskyi et al. 2021a). Wildfires essentially damaged protected areas (Zibtsev et al. 2020; Soshenskyi et al. 2021b). The catastrophic fires in 2020 showed that Ukraine, due to climatic changes and social and economic crises entered the list of countries with a high risk of uncontrolled wildfires (Zibtsev et al. 2020; Soshenskyi et al. 2021a).

One of the key factors that influences fire behavior is fuel (Byram and Nelson 2015; Rollins 2009; Heisig et al. 2022). The forest ecosystems and their structure are considered as complexes of forest fuels. Understanding how stand structure and soil parameters affect fire behavior and intensity can improve prevention and suppression, fire hazard assessment, and forest fires behavior modeling (Dillon et al. 2015; Schuldt et al. 2020; Cardil et al. 2021). Many methods and approaches have been developed and applied to study fuels (Finney et al. 2011; Kalabokidis et al. 2016; Adaktylou et al. 2020; Alcasena et al. 2021).

In the Commonwealth of Independent States (CIS) region, several scientists (Melekhov 1947; Nesterov 1949; Vonsky 1976; Volokitina and Sofronov 2002) have studied fuels and suggested different classifications. However, the approach applied by Kurbatsky became the most popular (Kurbatsky 1970; Sofronov et al. 2005). Kurbatsky's scientific approaches are currently used in Russia (Valendik et al. 2014) and Belarus (Klimchik 2018) to create natural fire hazard and forest fuel maps (Volokitina and Sofronov 2002). Several fuel classifications were based on spatial distribution in forests and ignition capacity as well as its contribution to the combustion process. According to that classification, all forest fuels are divided into six groups: (1) mosses and lichens, fine plant debris; (2) grasses and semi-shrubs; (3) undergrowth and understory; (4) forest litter and peat; (5) firewood; (6) needles, pine twigs. This approach only enabled to estimate fuel load for individual forest areas. However, there is currently no system that can use final outputs (fuel load) from that fuel assessment methodology in the fire spread modeling process or in the regional fuel model development (Sofronov et al. 2005; Klimchik 2018).

In the United States and some European countries, a different classification is widely used, according to which fuels are divided into two major groups: living and dead fuels (Byram and Nelson 2015; Fosberg 1970). Whereas the moisture content barely varies in living fuels during the day, the dead fuels dry along the day depending on their moisture (Fosberg 1970; Byram and Nelson 2015). This fuel classification method has been improved and used to quantify three general components of fuel complex: dead and down woody debris (DWD), duff and litter, and understory vegetation (Brown 1972). Biomass estimations of dead and down woody debris are collected for the size classes that fire scientists have found important for predicting fire behavior and effects (Fosberg 1970; Brown 1972). Experimental studies have shown that temporary retention of fuel moisture (time-lag) depends on their size (diameter). Due to this feature, fuels are divided into four size classes: (1) 1-h—$d=<0.6$ cm (light), (2) 10-h—$d=0.6–2.5$ cm (medium), (3) 100-h—$d=2.6–7.5$ cm (heavy), and (4) 1000-h—$d=7.6–20$ cm (very heavy) (Fosberg 1970; Brown 1972). Duff and litter are assessed by measuring the depth of the duff/litter profile down to the mineral soil and estimating the percent of total duff/litter depth that is litter (Brown 1972; Anderson 1982; Lutes et al. 2006). The biomass of living and dead, woody, and nonwoody understory vegetation is estimated based on estimations of cover and average height. Thus, fuels are combined into complexes and next to the fuel models. The data, which was collected using the methods described above, could be scaled up over large areas of forest and non-forest landscapes and used to model fire behavior and spread or to indicate potential fire effects (Rothermel 1972; Brown 1972; Deeming et al. 1977; Burgan and Rothermel 1984; Lutes et al. 2006). The fuel classification approach has been further developed. In combination with Rothermel surface fire spread model, it formed the basis of the US National Fire-Danger Rating System (NFDRS) (Deeming et al. 1977) and Standard Fire Behavior Fuel Models (Scott and Burgan 2005).

Fuel models, after their adaptation, have been successfully used in European countries (Majlingová et al. 2014; Majlingová et al. 2018; Kalabokidis et al. 2016; Alcasena et al. 2021; Heisig et al. 2022). Evaluation of landscapes as fuel complexes or models are suitable for being used in present advanced applications, such as forecasting natural fire hazards (Heisig et al. 2022) and burn probabilities (Kalabokidis et al. 2016) as well as assessing fire behavior and wildfire effects (Majlingová et al. 2018; Alcasena et al. 2021; Myroniuk et al. 2021).

The main issue in fuel model adaptation or local custom model development is a lack of field data about fuel loads and fuel complexes in Ukrainian landscapes assessed using standard field sampling and assessment methods (Lutes et al. 2006). Therefore, a further method to assess the basic fuel is suggested in the present study. This assessment method will serve as basis for the new set of national fuel models in Ukraine and integrates numerous data resources to estimate the potential fire hazard and behavior under different weather and fuel treatment scenarios in the Ukrainian Polissia. The purpose of the study is to find out the dependences between litter, duff, and herbs fuel loads in pine forests depending on the forest type and forestry indicators of the stand. Based on the results, build models for estimating forest litter loads for the main forest types of Polissia.

Material and methods

Data collection

A series of temporary sample plots (TSPs) were established in typical pine stands of Rivne and Kyiv Oblasts of Polissia of Ukraine. Pine forests constitute 64.5% of the forest stands of this region, growing mainly on relatively poor soils with varying humidity (Marynych 1993). In addition, these pine stands are characterized by a high natural fire hazard (Zibtsev et al. 2019; Voron et al. 2018a, b; Myroniuk et al. 2021). The study of litter, duff, and herbs fuel's structure and features of fuel accumulation was carried out in pine forests of different ages within wet and fresh soil conditions. Study was focusing primary on litter, duff, and herb fuels: litter, FWD, CWD, live fuel (grasses). Aerial fuel was not investigated (crown fuel). There was practically no natural renewal in the study plots due to this natural renewal and bushes was not investigated in the following article.

The forest mensuration parameters of the pine stands in the TSPs are displayed in Table 1.

TSPs were established to describe forest stands features in accordance with the generally accepted methods outlined in the "SOU 02.02–37-476:2006 – Trial Forest Management Areas. Temporary sample plots. Laying method." When establishing sample plots, we described the forest areas according to the generally accepted methods of forest mensuration (Anuchyn 1982). On each TSPs using FIREMON methodology (Lutes et al. 2006), five transects for the assessment of fine and coarse fuel debris were established. The methodology provides following division of fuel into the fraction: to 1 h less than 6 mm, the second group 10 h with a diameter from 6 to 25 mm, the third group 100 h with a diameter from 26 up to 75 mm, and the fourth group 1000 h with a diameter of 76 to 200 mm. In doing so, stand parameters as well as their components on the plots were measured: average height, diameter, and stand density. Stands age classes defined as 10-year age intervals (e.g., 1–10 years—I age class, 11–20 years—II age class, etc.).

All forest sites in Ukraine are classified by soil moisture level and soil fertility status (Pogrebnyak 1955). Soil moisture scale uses 6 classes from 0 to 5: 0—Very dry, 1—Dry, 2—Fresh, 3—Moist, 4—Wet, 5—Very wet. Soil fertility status uses 4 classes: A—poor), B—fairly poor, C—fairly rich, D—rich. Site conditions are formed by combining soil fertility and moisture (for example A_1). Pine forests are formed by*Pinus sylvestris L* in Polissia, distributed by forest types as shown in Table 2. As can be seen, 89.5% of all Scots pine forests are growing in condition of A_2, B_2, B_3, and C_2. Plot location was selected systematically to cover all age groups and forest types within a condition of A_2, B_2, B_3, and C_2.

Forest litter and duff loads were estimated in the analyzed forest stands. For that purpose, small sampling plots in each stand (a rectangle with a surface 1 m^2) were established. A sampling of litter was conducted upon its formation in July–August before needles fall. In this study, it was assumed that forest litter consists of two layers of mineralization: the litter layer (litter) and the semi-decomposed layer (duff). The litter load was determined according to the method described by Rodin and Bazilevich (1965) (Rodin and Bazilevich 1965). Each layer (litter and duff) was collected and weighed separately in the field. On the plots before sampling, the height (thickness) of forest fuel layers was measured in addition to forest regeneration and undergrowth; then, grass and bushes were cut. After that, litter, leaf debris, mosses, and lichens were collected. The collected samples were saved in plastic bags, and their mass was determined under field conditions. After that, these were dried in a drying cabinet within 24 h to a completely dry mass at a temperature of 100–105 °C.

Statistical analysis

For correlations calculated using general methods (Atramentova and Utevskaya 2007) in the first step of analysis, we checked all available variables (both connected with stand characteristic—DBH, relative density, stock, and height as well as variables connected with fuel characteristics—litter, duff, CWD, FWD live grass loads) to define type of connections and to find out what variables correlate with each other. To analyze difference between groups of SP that have different forest type and did not have a normal distribution, we used generalized linear mixed models including random effects of SP; for this purpose, we use "lme4" R package (https://tinyurl.com/mxc4t3wb).

To assess the significance of individual variables on which the variation of fuel loads depends, the random forest algorithm was used; for variable selection, we used two parameters: the percent increase in mean squared error (%IncMSE) and the Gini impurity index (IncNodePurity) (Breiman 2001).

Cluster analysis was performed using k-means partitioning method and Calinski-Harabasz criterion (Calinski and Harabasz 1974; Milligan and Cooper 1985). For clustering, we used next input variables: stand age (years), stand stock (m^3/ha), DBH (cm), stand height H (m), relative density *P*, depth of litter and duff layer (cm), total litter and duff load (tons/ha).

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

Table 1 Forest mensuration parameters of the pine stands on TSPs

TSPs	Stand composition	Stand age, years	DBH (cm)	Average height (m)	Relative density	Stand Stock, m^3/ha	Forest type
1	100% Scots pine	11	3.6	3.2	0.83	30.3	A_2
2	100% Scots pine	15	5.0	5.5	0.72	65.0	A_3
3	100% Scots pine	15	6.3	6.0	0.81	83.1	B_2
4	100% Scots pine	22	6.7	6.9	0.79	107	A_3
5	100% Scots pine	23	7.8	9.0	0.76	120.5	B_2
6	90% Scots pine 10% silver birch	27	15.2	11.3	0.7	175.0	B_3
7	70% Scots pine 20% silver birch 10% common oak	30	11.1	10.3	0.75	160.5	B_2
8	100% Scots pine	30	7.4	9.5	0.76	143.4	A_2
9	100% Scots pine	33	16.2	15.4	0.81	318.0	B_3
10	100% Scots pine	34	9.1	12.9	0.84	232.0	B_3
11	100% Scots pine	42	15.2	16.1	0.77	345.3	A_2
12	100% Scots pine	47	15.7	15.6	0.83	315.9	A_2
13	80% Scots pine 20% silver birch	50	17.7	14.8	0.74	177.0	A_3
14	100% Scots pine	51	17.4	18.0	0.78	355.7	B_2
15	100% Scots pine	54	23.5	24.6	0.83	539.0	B_3
16	100% Scots pine	55	21.0	18.3	0.79	349.5	A_2
17	100% Scots pine	62	20.4	19.7	0.75	342.6	A_2
18	100% Scots pine	69	25.6	27.6	0.83	466.3	B_2
19	100% Scots pine	69	20.2	19.4	0.74	403.0	A_3
20	100% Scots pine + silver birch + common oak	74	27.4	24.5	0.83	402.0	B_3
21	100% Scots pine	74	25.9	24.8	0.74	489.2	B_2
22	100% Scots pine + common oak	79	23.9	27.9	0.82	491.0	B_3
23	100% Scots pine	79	25.7	24.6	0.82	415.2	B_2
24	100% Scots pine + silver birch	80	29.6	23.5	0.73	367.7	A_2
25	100% Scots pine	94	32.9	27.4	0.71	441.2	B_2
26	100% Scots pine + silver birch + common oak	99	40.0	28.4	0.61	451.0	B_3
27	90% Scots pine 10% silver birch	116	31.2	24.9	0.41	543.9	B_2
28	100% Scots pine	125	34.7	26.4	0.61	396.0	A_2
29	100% Scots pine + common oak	139	46.1	31.4	0.51	380.0	B_3

Note: +, up to 5% in stand composition

$$Rv = M_{mp}/M, \tag{1}$$

where M_{mp}—mortmass of forest litter, $\text{t} \times \text{ha}^{-1}$, and M—trunk stock in the bark of a stand $\text{m}^3 \times \text{ha}^{-1}$.

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

$$Rv = a_0 \times x^{a1} \times x_n{}^{an}, \tag{2}$$

where Rv—dependent variable (conversion rate for litter load), a_0, a_n—regression coefficients, and x, x_n—independent variables.

We developed 2 models: “litter and duff load in pine forests growing in fresh conditions” and “litter and

Table 2 Distributions of Scots pine forests by forest types in Ukrainian Polissia

Forest type	Area, Ha	Share, %
B_2	16,351,043	42.0
B_3	7,461,593	19.1
A_2	4,753,218	12.2
C_2	4,688,341	12.0
C_3	1,626,901	4.2
Other 17 forest types	4,089,614	10.5
Total	38,970,710	100.00

duff load in pine forests growing in wet conditions." Dependent variable in both cases was a total litter and duff load (t/ha), and predictors are as follows: H—tree stand height, P—relative stand density, A—age of the stand.

Thus, the litter stock will be calculated due to the following dependence:

$$M_{\mathrm{P}} = Rv \times M \tag{3}$$

where M_{P}—forest litter stock in absolutely dry conditions (tons), and M—trunk stock in the bark (m^3/ha).

Results

In the pine forest stands of Polissia, the litter stock varies from 15.5 t/ha to 140 t/ha, and its thickness ranges from 3.4 to 12.9 cm. It was found that forest litter stocks increased with the age of the stand, and a moderate direct correlation was fit between the forest litter stock and the age of the stand ($r = 0.61$; $p = 0.05$). Stocks of fine woody debris (FWD) and forest ground vegetation did not vary significantly with the age of the forest stand (Table 3).

Table 3 Distribution of litter, duff, and herb fuel stocks by fractional composition

TSPs	Age, years	Forest type	FWD load, t/ha			Live herbs, t/ha	Litter-duff load, t/ha	Depth, cm
			1 h	10 h	100 h			
1	11	A_2	0.6	0.3	0.3	0.2	50.1	7.8
2	15	A_3	0.6	0.1	0.1	12.3	15.5	5.0
3	15	B_2	1.2	0.4	0.0	0.1	16.0	3.4
4	22	A_3	0.4	0.4	0.3	11.7	73.7	10.9
5	23	B_2	1.2	0.4	0.3	0.1	35.0	4.6
6	27	B_3	0.8	0.8	0.3	0.0	49.1	9.4
7	30	B_2	1.1	1.7	0.0	0.2	77.5	10.0
8	30	A_2	0.9	0.5	0.3	10.9	45.9	8.5
9	33	B_3	1.3	2.2	1.5	2.2	52.3	5.8
10	34	B_3	1.5	1.9	1.5	1.3	60.6	11.7
11	42	A_2	1.7	1.9	0.5	1.1	51.0	5.6
12	47	A_2	1.9	1.9	0.0	0.6	62.2	8.1
13	50	A_3	1.9	0.5	0.0	4.2	70.4	9.5
14	51	B_2	1.2	1.5	0.5	1.5	72.7	6.6
15	54	B_3	1.4	1.9	1.6	3.5	103.2	11.7
16	55	A_2	1.1	1.0	1.4	9.4	46.8	6.5
17	62	A_2	1.5	0.5	0.0	4.0	42.7	7.2
18	69	B_2	0.8	0.5	0.3	4.5	79.8	10.4
19	69	A_3	0.8	1.0	0.7	5.6	91.4	11.7
20	74	B_3	1.0	0.7	0.2	3.4	98.7	12.2
21	74	B_2	1.2	0.8	0.6	2.7	71.8	11.4
22	79	B_3	0.5	0.3	0.3	7.7	71.7	11.9
23	79	B_2	0.5	1.5	0.8	5.3	39.4	6.8
24	80	A_2	0.5	0.1	0.6	7.4	85.0	12.2
25	94	B_2	0.9	0.8	0.3	6.1	47.7	9.6
26	99	B_3	1.1	1.3	1.1	1.8	116.7	12.9
27	116	B_2	1.5	1.8	0.0	1.3	60.6	10.9
28	125	A_2	0.5	0.1	0.5	12.6	58.8	7.2
29	139	B_3	1.1	0.7	0.7	2.7	140.0	18.1

Forest litter stocks in pine forests growing in wet conditions (hygrotop with index 3) significantly exceeded this indicator in pine forests growing in drier conditions (hygrotop with index 2) ($z = 1.91$; $p = 0.05$) (Fig. 1). At the same time, there was no significant difference in litter and duff load for pine forests growing in different soil fertility types (trophotops) ($z = 0.93$; $p > 0.05$) (Fig. 2).

The average stock of litter and duff in pine forests located in fresh and moist soil conditions did not actually differ until the age of 30–40 years (Fig. 3). In fresh conditions, forest litter stocks double by the age of 61–70 years (from 33 t/ha at the age of 15–20 years till 66.7 t/ha at the age of 61–70 years), after which there is a 15% decrease in litter stocks to 47.7–58.8 t/ha by the age of stand 120 years. A typical difference between pine trees located in wet soil conditions is the constant accumulation of fuels with the age due to slower decomposition. Litter stocks in young pine trees (under 40 years of age) are 15.4 tons/ha; in medium-aged (40–60 years) pine forests, stocks increase 8 times—up to 100–120 tons/ha; in mature (over 80 years) and overripe pine forests, stocks exceed 120 tons/ha.

Along with forest litter and fine woody debris (needles, twigs, cones, etc.), forest ground vegetation is essential

Fig. 1 Study area and sample plots' location

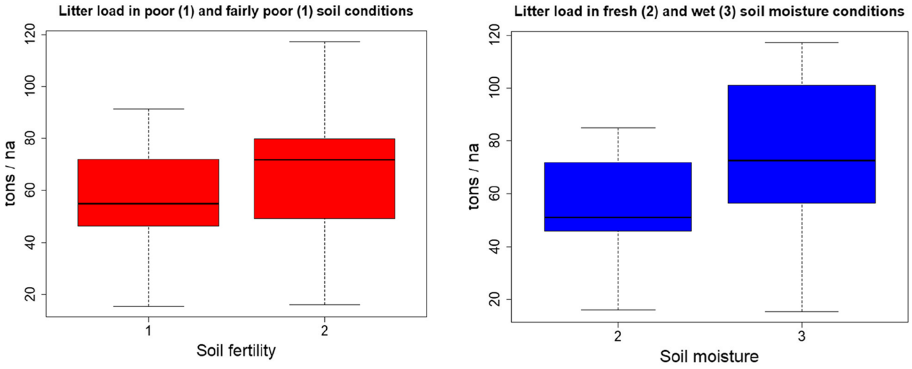

Fig. 2 Forest litter stocks in pine forests with different soil fertility (left) and moisture (right) conditions

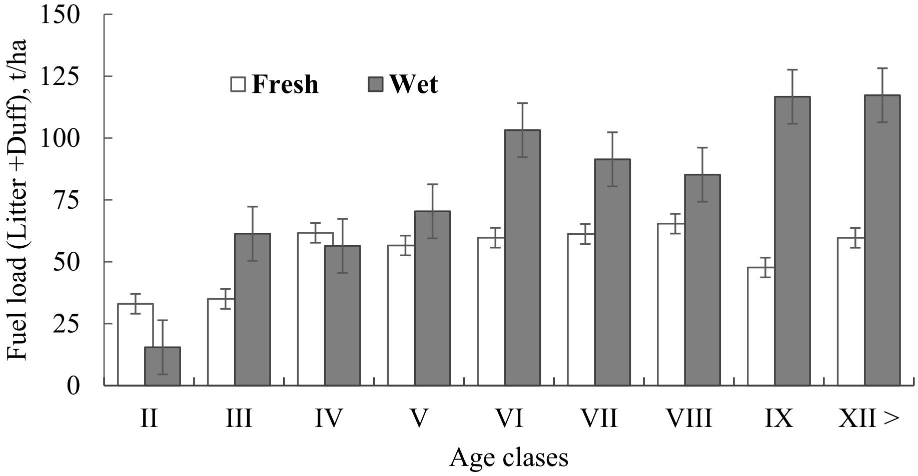

Fig. 3 Changes in forest litter stocks with the age

for the surface forest fuel complex formation. It is the forest ground vegetation that can be the main conductor of combustion in forest stands of low relative density and closeness, where an increase in sunshine under forest stand canopy provokes intensive development of grassy vegetation. In wet coniferous forests, the ground vegetation is formed by mosses and in wet fairly poor soil conditions—*Pleurozium schreberi* (Brid.) Mitt, *Dicranum polysetum* Sw., *Vaccinium myrtillus* L., and *Vaccinium vitis-idaea* L. Forest fuel stocks of forest ground vegetation were more dependent on the type of growing conditions. Thus, GLMM was performed among the studied groups (types of soil richness and wetness); a statistically significant difference was found for stands that have different soil richness ($z = -2.94$; $p = 0{,}003$). At the same time, there is no statistically significant difference in forest ground vegetation load connected with soil wetness ($z = 1.04$; $p = 0{,}29$). So, the average forest ground vegetation stocks were as follows: in fresh poor soil conditions (A_2)—5.78 t/ha; in wet poor soil conditions (A_3)—8.45 t/ha; in fresh fairly poor soil conditions (B_2)—2.44 t/ha; in wet fairly poor soil conditions (B_3)—2.84 t/ha. And the main driver of forest ground vegetation load was soil richness. Larger stocks of forest ground vegetation accumulated in the wet coniferous forests of Polissia. Such differences can be explained by predominance of mosses in the composition of subsurface cover of wet coniferous forests and in fresh and wet fairly poor soil conditions—*Pleurozium schreberi* (Brid.) Mitt, *Dicranum polysetum* Sw., *Vaccinium myrtillus* L., and *Vaccinium vitis-idaea* L.

Litter stock correlates with increase in taxation indicators of stands and its stock (stand stock $r = 0.65$, average height of the stand $r = 0.59$, DBH $r = 0.65$, A—age, years $r = 0.61$, $p = 0.05$) (Table 4). With the relative density of

Table 4 Correlation matrix of different forest fuel fractions' dependence on taxation indicators of the stand

Variable	*A* stand age, years	DBH, cm	*H* average height (m)	*P* relative density	Stand stock, m^3/ha	1 h	10 h	100 h	Live herbs	Litter and duff
A	1.00	**0.96**	**0.91**	**−0.66**	**0.77**	−0.10	−0.03	0.09	0.15	**0.53**
DBH	**0.96**	1.00	**0.94**	**−0.58**	**0.80**	−0.07	0.02	0.21	0.06	**0.62**
H	**0.91**	**0.94**	1.00	**−0.37**	**0.91**	−0.06	0.09	0.25	0.07	**0.60**
P	**−0.66**	**−0.58**	**−0.37**	1.00	−0.13	−0.02	0.03	0.16	−0.02	**−0.22**
Stand stock	**0.77**	**0.80**	**0.91**	**−0.13**	1.00	−0.10	0.01	0.18	0.13	**0.50**
1 h	−0.10	−0.07	−0.06	−0.02	−0.10	1.00	0.59	0.01	**−0.57**	0.00
10 h	−0.03	0.02	0.09	0.03	0.01	**0.59**	1.00	0.42	**−0.52**	0.16
100 h	0.09	0.21	0.25	0.16	0.18	0.01	**0.42**	1.00	0.03	0.28
Live herbs	0.15	0.06	0.07	−0.02	0.13	**−0.57**	**−0.52**	0.03	1.00	−0.11
Litter and duff	**0.53**	**0.62**	**0.60**	**−0.22**	**0.50**	0.00	0.16	0.28	−0.11	1.00

A, stand age, years; *DBH*, diameter at the breast height, cm; *H*, average stand height, m; *P*, relative density

Statistically significant correlation coefficients (*p*-value < 0.05) are highlighted in bold forest stands decrease, a decrease in the mass of forest litter can be traced (inverse correlation $r = -0.31$ $p = 0.05$). No significant correlations were found between the forest ground vegetation stock and taxation indicators of stands. A similar trend can be traced with FWD forest fuels (1 h, 10 h, 100 h)—no reliable relationships with the stand parameters were found.

In wet forest types, differences in average FWD stocks become less noticeable: wet—2.7 t/ha; fresh—2.4 t/ha. Also, no statistical differences were found when comparing the average FWD stock in coniferous forest (poor soils); here, they reach 2.1 t/ha, while in fairly poor soil conditions (richer soils), they reach 2.7 t/ha. Despite this, GLMM was used also to compare FWD stocks in forest stands of varying degrees of soil moisture and fertility. FWD stocks were found to no significantly difference in fresh and wet conditions (1 h, 10 h, 100 h) (Fig. 4).

Cluster analysis was applied to analyze and compare the forest litter stock in forest stands of different degrees of soil moisture. The results of cluster analysis showed a discrepancy in forest litter stocks under wet and fresh forest conditions, which are combined into three clusters with a high coupling distance in the feature space. Forest stands that differ in soil moisture showed significant differences both in direction of the litter stocks formation and absolute indicators of stocks in stands of different ages, which became the basis for 3 clusters allocation (Fig. 5).

Based on the cluster analysis results, three clusters were identified (Table 5); the main differences in which

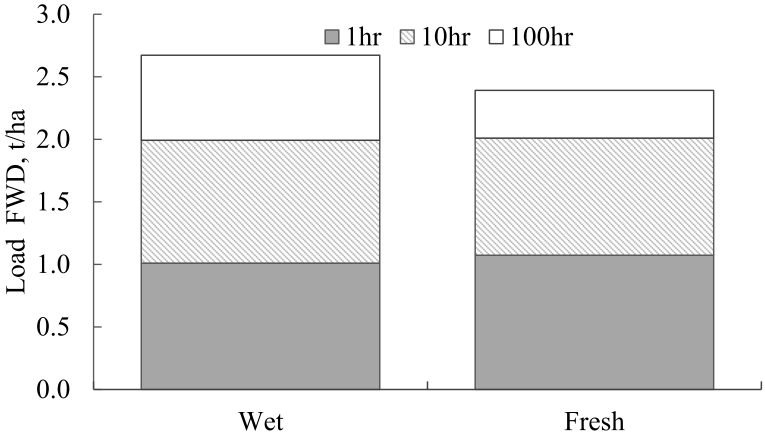

Fig. 4 Load of different fractions of forest fuel

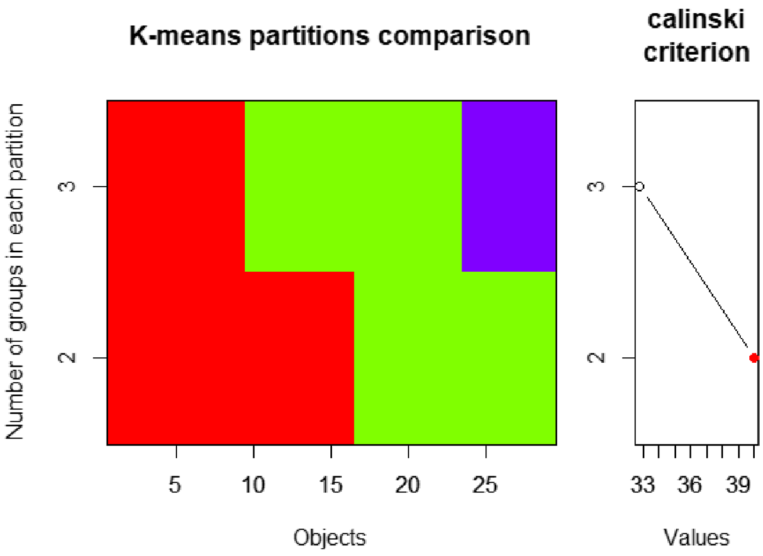

Fig. 5 Cluster plots of forest fuel in different forest stands of Polissia

Table 5 Clusters characteristics (cluster centers)

Cluster	Soil moisture	Age, years	Stand stock, m^3/ha	DBH, cm	H, m	Relative density	Depth, cm	Litter-duff load
1	Wet	87.0	323.6	31.4	25.7	0.7	12.1	105.5
2	Wet/fresh	40.5	151.2	14.7	13.8	0.8	6.7	40.9
3	Wet/fresh	64.8	213.8	20.7	19.5	0.7	9.2	70.4

Table 6 The most important variables for litter + duff modeling

Variable	The percent increase in mean squared error (%IncMSE)	Gini impurity index (IncNodePurity)
Age, year	5.187	3109.1
DBH, cm	8.178	3304.4
H, m	8.891	3503.5
P	1.309	2352.3
Stand stock, $m^3 \times ha^{-1}$	7.232	3249.0

A, stand age, years; *DBH*, diameter at the breast height, cm; *H*, average stand height, m; *P*, relative density

are as follows: type of forest growing conditions and age of the stand. Thus, stands up to the age of 50 years (cluster 2) have no significant differences in litter stocks (litter stocks in wet and fresh stands tend to increase with the age of stands). After the age of 50 years, the differences in forest fuel stocks in fresh and wet conditions start significantly differing (cluster 1 and cluster 2 are highlighted) (Table 5).

Model development for estimating forest litter stock, taking into account stand stock and forest conditions

Based on the results obtained from random forest analysis obtained (Table 6), based on the percent increase in mean squared error and Gini impurity index, main variables that can be used in forest fuel stock modeling were defined.

Indicators *H*, *P*, and *A* reflect close relationship between forest fuel stocks and taxation indicators, so they are best suited for including them in the forest fuel model development. So, the model for determining the conversion rate *Rv* to assess the total mortmass of the forest litter in pine forests growing in fresh conditions is as follows:

$$Rv_{fresh} = 22.3 \times H^{0,17} \times P^{-1,4} \times A^{-1,28} (R^2 = 0.93, p = 0.05) \quad (4)$$

To estimate the total mortmass of forest litter in pine forests growing in wet conditions, a model is built (R_{wet}) for calculating the conversion rate:

$$R_{wet} = 21.3 \times H^{0,27} \times P^{-2,51} \times A^{-1,31} (R^2 = 0.91, p = 0.05) \quad (5)$$

The models proposed allow estimating approximate forest litter stock at the regional level for the natural zone of Polissia of Ukraine using official forestry mensuration databases of Ukrainian State Project Forest Management Production Association, PA “Ukrderzhlisproekt.”

Discussion

According to the study in the pine forest stands of Polissia, the litter stock varies from 15.5 to 140 tons/ha, which significantly exceeds the volumes established by other authors, for pine forests growing in more dry conditions of the forest-steppe of Ukraine, where the forest litter stock ranges from 17.2 to 67.5 t/ha (Voron et al. 2018a, b; Voron et al. 2018a, b; Sydorenko 2019). Differences were also found in the thickness of the litter and duff layers: 3.4–12.9 cm in Polissia and 1.4–10.4 cm in the forest-steppe of Ukraine. Taking into account such differences in both forest fuel stock and climatic indicators of these natural zones, forest fuels in typical pine forests of Polissia (growing in wet conditions) will need longer in order to be dried until the burning state, but they are reaching the state of pyrological ripeness (readiness of forest fuel to ignite). In the forests of Polissia, wildfires will have a stronger post-fire effect: impact on the post-pyrogenic development of stand (post-pyrogenic mortality, deterioration of the sanitary conditions of stands) and the most part of the carbon release when burning out more forest fuels. Wildfires will mostly have the character of smoldering fire, which will also affect the complexity of fire extinguishing. Furthermore, this effect will be stronger in the mature stands with moist and wet soil conditions (Voron et al. 2018a, b; Sydorenko 2019).

The main reason for these divergences is due to that the differences in the climatic indicators of these two natural zones (forest-steppe is characterized by significantly less precipitation during the year: 450–550 mm, with the evaporation of 550–750 mm and higher average annual air temperatures). As a result, in forest-steppe conditions, pine forests grow in drier conditions (fresh forest).

In contrast, in Polissia, in wet conditions, wet fairly poor soil conditions predominate (Voron et al. 2018a, b; Voron et al. 2018a, b; Sydorenko 2019).

Such differences in climatic indicators are the factor in slowing down the process of forest litter destruction, which, according to the results of our research, tends to be accumulated with the age. This process does not stop even until the stand age of 120–130 years (see Table 2). In the forest-steppe, on the contrary, there is an increase in litter stock up to a certain age (up to 80–90 years), when the productivity of the forest stand is maximum, and supply of a new biomass with precipitation compensates for the process of destruction and rotting (Voron et al. 2019; Sydorenko 2019). But with the age and a decrease in relative density in forest-steppe conditions, litter stocks start decreasing due to a decrease in the stand stock and their relative density (variables that indirectly affect the flow of litter) (Sydorenko 2019). In the present study, we found the same trend in two groups of soil moisture: fresh and wet types. In Polissia—fresh types of forest—growing conditions tended to form forest litter stock close to those in the forest-steppe, while wet types had their own unique trend (continuous accumulation of forest fuel stock throughout the entire period of forest stand ontogenesis). Voron came to the similar conclusions (Voron et al. 2018a, b), noting that wet forest types accumulate larger forest litter stock. A study of forest fuel complexes in Puerto Rico (Brandeis and Woodall 2008) revealed that forest litter load decreased from wet to dry forest soil conditions. Brandeis and Woodall (2008) found that duff amounts did not vary greatly by life zone except for subtropical wet forests (6.35 Mg ha^{-1}), which had greater amounts of duff than values found in subtropical dry forests (1.41 Mg ha^{-1}, $p=0.0251$). Litter amounts, however, clearly decreased as the life zones became drier. Subtropical dry forests had less litter (3.54 Mg ha^{-1}) and subtropical wet (12.76 Mg ha^{-1}, $p=0.0001$) forests (Brandeis and Woodall 2008). So, the "hygrotop" indicator is one of the key parameters in modeling litter and duff stocks and the processes of forest litter accumulation and destruction.

Forest fuel stocks of the forest ground vegetation also depended to a greater extent on the type of growing conditions of each forest area, which is quite natural for the Polissia of Ukraine. Therefore, the main factors for the forest ground vegetation cover stock growth in the stands were the type of growing conditions (typical species composition of forest ground vegetation, which is formed depending on the type of growing conditions) and the decrease in the relative density of the stands (under such conditions, forest ground vegetation stock grew up to 12.6 t/ha).

In wet coniferous forests, significantly larger forest ground vegetation stocks were accumulated (2.9 times) than in fairly poor soil conditions. Large forest ground vegetation stocks in the coniferous forests were caused by the lack of undergrowth and forest understory and, as a result, the penetration of more light under the forest stand cover.

Analysis of FWD stocks of different fractions in stands of different ages and under different moisture conditions did not reveal any significant differences. The main factor, which influences the increase in the FWD stock (10-h and 100-h fractions), is the stand stock. Thus, the FWD accumulation largely depends on the stand productivity and practically does not depend on the trophic nature of the stands, moisture content of the site, and age of the forest stand.

According to the results of Kurbatsky's research (Kurbatsky 1970, 1974), the volumetric weight of the litter varies significantly (from 36 to 110 g/dm^3), depends on the forest site type, and decreases with increasing humidity of the growing area. In the present study, such conclusions could not be confirmed. In contrast, the density of litter increases as the soil moisture index and age of stand increase: from 7.75 g/dm^3 at the age of 10–20 years up to 218 g/dm^3 at the age of 120–140 years. In fresh conditions (drier conditions), the litter density increases from 5.44 (10–20 years) up to 103.7 g/dm^3 at the age of 80. A typical feature of pine forests in fresh conditions is their increase only up to the age of 80 years, after which it rapidly decreases by 2–2.5 times (up to 42–66 g/dm^3) at the age of 120 years. These results are in line with the studies conducted in fresh coniferous forests and fairly poor soil conditions of the forest-steppe (Sydorenko 2019). This study also describes the variability trend of the volume mass values in the Left-Bank forest-steppe: 30.6–97.3 g/dm^3. The author related the change in the litter density to the change in the age of stands, soil conditions, relative density, stand bonitet, etc. So, if the average volume mass of litter is 30.6–36.2 g/dm^3 in pine forests of the II–III age class, then in pine forests of the VI–VIII age class, it is 74.8–97.3 g/dm^3, so it grew 2.1–3.2 times. The pyrological significance of the litter stocks growth and volume mass varies. When stocks increase, the burning time and temperature increase, while density increase slows down the burning rate.

The suggested mathematical models (4, 5) enable to estimate approximately forest litter stock at the regional level (Polissia natural zone) using national taxation databases of PA "Ukrderzhlisproekt." The results of such modeling can be used to assess the impact of fires on the forest ecosystems (fire intensity, potential fire behavior, post-pyrogenic decline, etc.) and estimate the release of carbon dioxide during fires.

Considering the results of cluster analysis, the main differences in clusters that characterize the entire complex of forest fuels are the type of forest conditions and the age of stands. Thus, before 50 years, litter stocks in wet and fresh stands change synchronously; after 50 years, differences in forest fuel stocks in fresh and wet conditions start significantly differing. In view of these results, it is advisable for Polissia of Ukraine to start creating three custom models of fuels that can be used in program products (FlamMap) to accurately predict the behavior of fire in these conditions.

Currently, the FirEUrisk project has developed a global map of fuels for the territory of the European Union (Aragoneses et al. 2022); the map has a spatial difference in 1 km^2 and is fully adapted to the European conditions. However, a set of custom models should be developed for Ukrainian conditions, taking into account the specifics of Ukrainian landscapes and the forest fuel complexes that are form in them. One of the ways to integrate national custom models with the European-wide fuel map is to add an additional third "national" level of models to FirEUrisk fuel types.

It is worth noting that climate change, forest use, and military operations taking place in Ukraine have a significant impact on natural fire hazards and fuel dynamics. The authors (Balabukh and Zibtsev 2016; Shevchenko et al. 2014) note that due to climate changes in the territory of Ukraine, negative changes should be expected, such as an increase in air temperature, an increase in the duration of the fire-hazardous period, the recurrence and duration of dry periods, a change in water resources local runoff, and other hydrometeorological phenomena. Since 2013, changes in climate regimes have already affected the decrease in the level of groundwater in Ukrainian Polissia (Balabukh and Zibtsev 2016), which led to the massive drying of Common oak, birch, and Scots pine stands (Zhezhkun and Porohnyach 2020). In the Ukrainian Polissia, conditions are forming that will be suitable for growing mainly Scots pine stands (Shvidenko et al. 2017), which will significantly affect the dynamics of surface fuels, natural fire hazards and fire regimes.

Also, the Russian war against Ukraine has a direct impact on the dynamics of landscape fires and forest and land use changes. After the full-scale military invasion, millions of hectares of Ukrainian forests were directly and indirectly affected by the military operations. After the partial occupation of Luhansk and Donetsk regions by Russia in 2014–2021, as a result of the war in 2022–2023, significant areas of mined and explosively contaminated forests appeared on the territory of Ukraine (Zibtsev et al. 2023). This had a significant impact on the nature of forest use and the dynamics of surface fuels in forest and other natural landscapes adjacent to them. In these conditions, there is a need to develop a holistic and systematic approach to the management of forests and fuels in the territories contaminated by explosive objects and unexploded ammunition, which will increase the readiness and safety of both forestry personnel and the local population and save valuable ecosystems from catastrophic Wildland fires (Zibtsev et al. 2023).

Conclusions

Significant forest fuel stocks in the pine forests of Ukrainian Polissia are accumulated in the stands growing on wet types of TSPs such areas are found mainly on the lowlands and in micro-depressions. In such stands, the accumulation of fuel stock (litter + duff) increases with the age and continues throughout the entire period of stand ontogenesis. Thus, the humidity index of the sites is one of the key parameters in the litter and duff stocks modeling.

The forest fuel stocks of the forest ground vegetation vary within 2.62–6.67 tons/ha and depend on the closeness of the stand and soil trophic nature.

It was found that FWD stocks in the pine forests of Polissia vary within 0.8–4.9 t/ha. FWD stocks were more correlated with stand productivity (stock and relative density of the stand). There was no significant statistically big difference in FWD stocks as a whole and individual fractions (1 h, 10 h, 100 h) depending on the soil trophic nature and moisture content.

The density of fuels (litter + duff) varies significantly and depends on the forest sites and increases with increasing humidity of the site: from 7.75 g/dm^3 at the age of 10–20 years to 218 g/dm^3 at the age of 120–140 years. In fresh conditions (drier conditions), the litter density increases from 5.44 (10–20 years) to 103.7 g/dm^3 at the age of 80 years. The results obtained made it possible to develop mathematical models for estimating litter and duff stocks in the forests of Polissia and are the starting point for the national set of fuel model development for each nature zone of Ukraine.

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Authors' contributions
Serhii Sydorenko: conceptualization, methodology, validation, formal analysis, investigation, data curation, writing—original draft, writing—review and editing. Vasyl Gumeniuk: conceptualization, methodology, validation, formal analysis, investigation, writing—original draft, writing—review and editing. Felipe de Miguel-Díez: writing—review and editing, project administration. Olexandr Soshenskiy: validation, formal analysis, writing—original draft, writing—review and editing. Ihor Budzinskyi: resources, supervision, writing—review and

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Availability of data and materials
The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

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