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Analysis and forecasting of the scale and impact of forest fires on ecosystems of Ukraine

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Abstract. Forest fires are one of the most significant environmental problems that have a major impact on biodiversity and climate conditions. The purpose of the study was to investigate the impact of military operations on the ground cover in the area of the Bekhy forestry, which was disturbed by fire. It was revealed that for the period 2022-2023, 15 forest fires were recorded on the territory of the Korosten forest hunting enterprise of the state enterprise "Forests of Ukraine", while the total area covered by fires was 15.13 ha. Overall, the number of fires increased from 5 to 10, but the total area covered by fires decreased from 12.1 to 3.03 ha. At the site of fires in 2022, the pH level increased to lower horizons, with the highest values at microhills (7.55) and microdepressions (7.35). There was a slight increase in the organic carbon content in the upper humus horizon of soils (0.42% on microhills and 0.46% on microdepressions). Bekhy forestry suffered a large forest fire in May 2023, which covered an area of 1.2 ha. The fire hazard assessment of each quarter was carried out separately. In the 50th and 51st compartments, Scots pine was the most fire-prone type of plantings. The 2023 fire site also showed an increase in pH in the lower horizons, with the highest values in microhills (7.35) and microdepressions (7.55). The 2023 fire site showed a decrease in organic carbon content compared to the background sites, with minimal values in the lower parts of the soil profile (0.33% on microdepressions and 0.38% on microhills). The results of the study can be used to develop and implement environmental measures and programmes aimed at restoring forests damaged by fire

Keywords: mathematical modelling; probabilistic estimates; Bayes' theorem; carbon; soil profile; background plots

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Introduction

One of the main environmental challenges facing Ukraine is the destruction of forests in the north-eastern part of Zhytomyr Oblast due to forest fires. Forest ecosystems in Ukraine are important regulators of climate and biodiversity. The destruction of forests due to fires worsens the quality of soils, water resources, and threatens the existence of many species. The problem of the study is that the impact of the Russian-Ukrainian war contributes to an increase in the area of forests covered by the fire. During the full-scale Russian invasion of Ukraine, more than 3 million ha of forest were affected. According to the State Ecological Inspectorate, approximately 23.3 thousand ha of forests have been burned, some of which have been lost forever (Environmental terrorism of…, 2023).

O.V. Kratko & S.V. Kratko (2023) found that thousands of hectares of forest stands were damaged due to fires after the hostilities. According to the results of this study, it was noted that the most damaged areas were forests in the Luhansk Oblast. I.V. Rybalova *et al*. (2020) noted the largest excess of heavy metals in the soil of coniferous forests of the Chuguivskyi district of the Kharkiv Oblast was noted as a result of a forest fire, in particular copper, zinc, and manganese. According to the conclusions obtained, it was found out that for copper, the excess was 3.41 times, zinc – 2.87 times, and manganese – 2.24 times. E. Korotetska *et al*. (2022) reported the need for statistical analysis and forecasting of the state of forest resources in the Lviv and Kharkiv oblasts. It was established that as a result of a large number of fires, forest stands in the Kharkiv Oblast were in the worst condition compared to the forests of the Lviv Oblast.

A.S. Melnychenko (2023) identified the presence of a problem of chemical contamination in accidents with the release of toxic gases. It is recommended to use chemical neutralisers to maintain a high intensity of gas deposition from the atmosphere. I. Patsev *et al*. (2023) indicated the presence of a problem of mechanical and fire damage to forest lands in the Zhytomyr Oblast. They noted that during the military operations in the period from February 2022 in the Zhytomyr Oblast, 120,000 ha of forest were destroyed. B.V. Molodets (2019) addressed an issue related to the negative effects of wildfires that occurred in the USA from 1992 to 2015. As a result, a product for automated fire risk forecasting was developed. Problem raised in the study by S. Tiwari *et al*. (2022) consisted in the fact that an increase in the solubility of phosphorus in dust and ash occurred with a decrease in PH. It was noted that although acidic soils have a lower pH level, they may have a higher sorption capacity, which leads to a higher amount of phosphorus extracted compared to alkaline soils.

M. García-Carmona *et al*. (2022) outlined the problem of the risk of soil erosion after a forest fire. It was proved that the development of mosses significantly affected the physical and chemical properties of the soil after forest fires. R.E. Loeb & H. Mao (2021) noted that an increase in the pH level can lead to a decrease in reforestation for some tree species. It was found that applying fertilisers to increase the content of phosphorus, potassium, magnesium, and calcium did not lead to a change in natural recovery. D.B. Johnson *et al*. (2024) investigated the problem of increasing pH and decreasing carbon content in organic soil after a fire period. As a result of the research conducted by D.B. Johnson *et al*. (2024), forest fires can lead to complex changes in the composition of the soil microbial community. The content of polycyclic aromatic hydrocarbons at pyrogenic sites remained unexplored.

The purpose of the study was to determine the features of background areas and soils affected by a fire in the ground cover as a result of military operations. Research objectives: development of a mathematical model for predicting forest fires based on the Bayes' statistical mathematical model; investigation of soil degradation after fires.

Materials and Methods

During the soil contamination study, the methodology used was regulated by the State Standard of Ukraine DSTU 4287:2004 (2004), DSTU ISO 10381-2:2004 (2004). Field studies were conducted on sites located in the Bekhy forestry branch of the state enterprise (SE) "Forests of Ukraine" Korosten forest hunting enterprise (Korosten FHE), which is located in the north-eastern part of Zhytomyr Oblast.

Sections were excavated at each of the sites (30 sites in total). Soil samples were taken from each section along the soil horizons for further analysis. Soil samples were taken for analysis in the first half of August 2023. Samples were dried at room temperature in the shade. The soils were sifted through a sieve with holes of 0.25 mm and 1 mm, depending on chemical analysis. 15 fires were recorded in the branch of Korosten FHE for the period 2022-2023. The total area covered by the fires was 15.13 ha (Fig. 1).

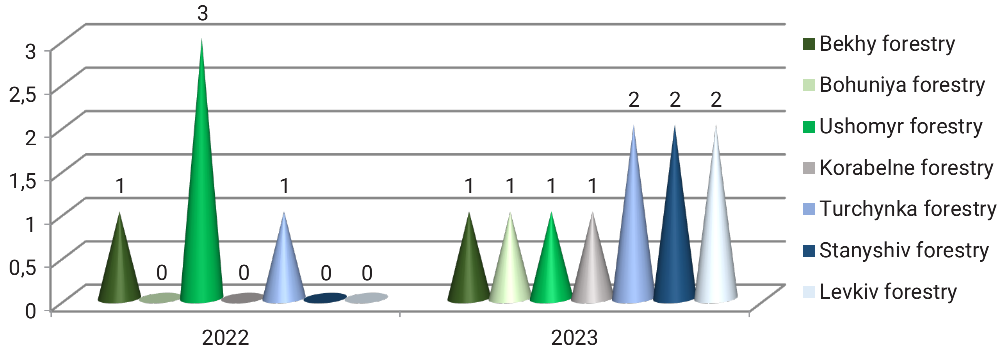

Figure 1. Dynamics of the number of cases of forest fires in the Korosten FHE branch of the SE "Forests of Ukraine" for the period 2022-2023

Source: compiled by the author

According to the Korosten FHE branch and the State Emergency Service of Ukraine in Zhytomyr Oblast, 5 fires were recorded in three forestries in 2022, covering an area of 12.1 ha. In 2023, 10 fires were registered on the territory of seven forest districts, however, compared to 2022, the area covered by fires has become three times smaller and amounted to 3.03 ha. The study used the Bayesian statistical model to improve the accuracy of predicting the occurrence of forest fires. Potentiometric method for studying the pH of an aqueous suspension on the Expert-01 ionometer (manufactured by Orion company, Ukraine). Titrimetric method for determining organic carbon according to I.V. Tiurin using phenylanthranilic acid. To determine the pH of water extraction by potentiometric method and the organic carbon content, 6 sites were studied: burned areas in 2023, areas affected by the fire in 2022, and background areas. Areas were selected on microrelief (microdepressions and microhills). 87 samples were selected at key sites based on the genetic horizons of soil profiles. The gradation of age groups of plantings by age was divided into the following categories:

- young stands (Y): plantings under 20 years of age;
- middle-aged stands (M): plantings aged from 21 to 40 years;
- ripening stands (R): plantings aged from 41 to 60 years;
- mature stands (Mat): plantings aged from 61 to 80 years;
- overripe stands (Ovr): plantings over 80 years of age.

The following calculations were carried out: organic carbon content by horizons and its subsequent averaging; pH content by horizons and its subsequent averaging; calculation of the probability of each hypothesis; calculation of the probability of the appearance of the attribute k_1 in compartment H_i. The area of forest lands of the Bekhy forestry district was divided into 120 compartments, so 120 hypotheses H1, H2, ..., H120 can be distinguished. The probability of each hypothesis was calculated using the equation (1):

$$P(H_i) = \frac{S_{H_i}}{S}, \qquad (1)$$

where: $\sum_{i=1}^{120} P(H_i)=1$; $P(H_i)$ – a priori probability of hypothesis H_i; S_{H_i} – area of the forestry compartment; S – total area of all the forestry compartments under study.

Calculation of the probability of occurrence of the attribute k_1 in compartment H_i was determined by equation (2):

$$P(k_{ij}/H_i) = \frac{S_{k_{ij}}}{S_{H_i}}, \qquad (2)$$

where: $P(k_{ij}/H_i)$ – probability of occurrence of the attribute k_i in compartment H_i; S_{kij} – forest area in the compartment; S_{H_i} – area of the forestry compartment.

The probability of fire occurrence was estimated using the Bayes' equation (3):

$$P(H_i/K) = \frac{P(H_i)\,P(K/H_i)}{\sum_{i=1}^{n} P(H_i)\,P(K/H_i)}, \qquad (3)$$

where: $P(H_i)$ – a priori probability of the Hi hypothesis; K – event characterised by a certain set of attributes k_1, k_2, ... k_v; n – total number of possible hypotheses; $P(H_i/K)$ – a posteriori probability of the Hi hypothesis after the results for the complex of attributes of the event K became known; $P(K/H_i)$ – probability of occurrence of the event K with the H_i hypothesis.

Results

The territory of the Korosten FHE branch was characterised by the Class 1 of fire danger. The estimated logging area for the main use for 2010-2018 was 63830 m³, of which: young coniferous species – 37220 m³, hardwood species – 12900 m³, of which 12900 m³ was in the oak working circle. For analysis, the Bekhy forestry department of the Korosten FHE branch was selected, where a large forest fire occurred in May 2023, covering an area of 1.2 ha (Fig. 2). The area of forests of the Bekhy forestry was 7602 ha.

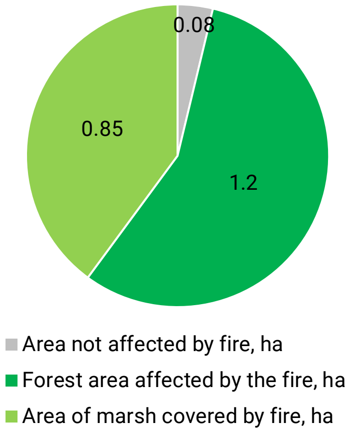

Figure 2. Analysis of the area of land plots covered by a fire in the Bekhy forestry in 2023
Source: compiled by the author

Using statistics, the fire hazard of each of the compartments throughout the territory of the Bekhy forestry was estimated and fire hazard classes were determined. To determine the probability of a fire in the forest, an area of 4 compartments was taken (50, 51, 60, 61), the total area of which was 270.4 ha with forest stands. According to equation 1, it was determined that:

$$P(H_{50}) = \frac{S_{H_{50}}}{S} = \frac{103}{270.4} = 0.38,$$

$$P(H_{51}) = \frac{S_{H_{51}}}{S} = \frac{80}{270.4} = 0.29,$$

$$P(H_{60}) = \frac{S_{H_{60}}}{S} = \frac{50}{270.4} = 0.18,$$

$$P(H_{61}) = \frac{S_{H_{61}}}{S} = \frac{40}{270.4} = 0.14.$$

To determine the risk of fire probability in each of the compartments, the following characteristics were determined: k_1 – composition of forest stands; k_2 – crop density; k_3 – age of forest stands; k_4 – type of forest conditions. Main forest stands of the Bekhy forestry: k_{11} – Scots pine (Sp); k_{12} – white birch (Wb); k_{13} – common oak (Co); k_{14} – black alder (Ba); k_{15} – aspen (A). For each of the compartments, the average value of Scots pine and common oak as a percentage was determined from the formula of rock composition. Table 1 shows the taxation characteristics of compartment 50.

Table 1. Taxation indicators for compartment 50

Stratum	Area, ha	Stand composition	Plantings age group	Relative stand density	Forest type
1	0.5	10Sp+Wb	5	0.7	B3 OP
2	7	10Sp+Wb	6	0.6	A2 P
3	8.5	7Sp3Wb+Co	8	0.7	C2 HOP
4	2	10Sp	3	0.7	B2 OP

Note: wet oak-pine subor (B3 OP); fresh pine forest (A2 P), fresh hornbeam-oak-pine sugrud (C2 HOP), fresh oak-pine subor (B2 OP)

Source: compiled by the author

Pine stands were the most fire-hazardous in compartment 50. Most of the territory of the compartment 50 contained Scots pine stands, the average value of which was 90%. Equation (2) is used to determine its average value for compartment 50:

$$P(k_{11}/H_{50}) = \frac{0.5*1+7*1+8.5*0.7+2*1}{103} = 0.15.$$

Table 2 shows the taxation characteristics of compartment 51.

Table 2. Taxation indicators for compartment 51

Stratum	Area, ha	Stand composition	Plantings age group	Relative stand density	Forest type
1	0.7	10Sp+Ba	5	0.8	B3 OP
2	9	8Sp2Wb+Co	6	0.9	C2 HOP
3	9.5	8Sp2Wb+Co	8	0.8	C2 HOP
4	3	10Sp	3	0.9	B2 OP

Source: compiled by the author

Pine stands were the most fire-hazardous in compartment 51. The average value of pine stands was 90%. Equation (2) is used to determine its average value for compartment 51:

$$P(k_{11}/H_{51}) = \frac{0.7*1+9*0.5+9.5*0.8+3*1}{80} = 0.19.$$

Table 3 shows the taxation characteristics of compartment 60.

Table 3. Taxation indicators for compartment 60

Stratum	Area, ha	Stand composition	Plantings age group	Relative stand density	Forest type
1	0.4	10Co+Ba	4	0.9	B3 OP
2	6	6Co4Wb+A	7	0.8	C2 HOP
3	5	6Co+4Wb+A	9	0.7	C2 HOP
4	8	10Co	4	0.6	B2 OP

Source: compiled by the author

Common oak stands were the most fire-hazardous in compartment 60. The average value of commonoakstandswas80%.Equation(2)isusedto determine its average value for compartment 60:

$$P(k_{13}/H_{60}) = \frac{0.4*1+6*1+5*1+8*1}{50} = 0.38.$$

Table 4 shows the taxation characteristics of compartment 61.

Table 4. Taxation indicators for compartment 61

Stratum	Area, ha	Stand composition	Plantings age group	Relative stand density	Forest type
1	0.3	10Co+A	6	0.8	B3 OP
2	5	6Co4Wb+Ba	8	0.9	C2 HOP
3	8	6Co4Wb+A	10	0.6	C2 HOP
4	9	10Co	7	0.4	B2 OP

Source: compiled by the author

Common oak stands were the most fire-hazardous for compartment 61. The average value of oak stands was 82%. Equation (2) is used to determine its average value for compartment 61:

$$P(k_{13}/H_{61}) = \frac{0.3*1+5*1+8*1+9*1}{40} = 0.55.$$

The most fire-prone areas were those with a stand density of 0.7, 0.8, and 0.9. According to the stand density, the following groups can be distinguished: k_{21} – density 0.7-1; k_{22} – density 0-0.6. There are medium-sized (1, 2, 3, and 4 strata) plantations in compartment 50. According to equation (2), the average value of stand density for compartment 50 was calculated:

$$P(k_{21}/H_{50}) = \frac{0.5+8.5+2}{103} = 0.1.$$

On the territory of compartment 51 there are high-quality (1, 2, 3, and 4 strata) plantings. Using equation (2), the average stand density value for compartment 51 was calculated:

$$P(k_{21}/H_{51}) = \frac{0.7+9+9.5+3}{80} = 0.27.$$

On the territory of compartment 60, there are high-density (1st and 2nd strata) and medium-density (3rd and 4th strata) stands. Using equation (2), the average stand density value for compartment 60 was calculated:

$$P(k_{21}/H_{60}) = \frac{0.4+6+5}{50} = 0.22.$$

On the territory of compartment 61 there are high-density (1st and 2nd strata) and medium-density (3rd stratum) and low-density (4th stratum) stands. Using equation (2), the average stand density value for compartment 61 was calculated:

$$P(k_{21}/H_{61}) = \frac{0.3+5}{40} = 0.13.$$

The following age groups are distinguished: k_{31} – age groups 2 and 3 (young stands of Class 1 and 2 up to 40 years); k_{32} – age groups 4 and 8 (others over 40 years old). In compartment 50, on average, by age group, plantings belong to ripening stands (71-80 years), which was 90%. Fire hazard class 1 – presence of plantings of age groups 2 and 3 (4th stratum):

$$P(k_{31}/H_{50}) = \frac{S_{k_{31}}}{S_{H_{50}}} = \frac{2}{103} = 0.01.$$

Fire hazard classes 2-4 – age groups 4-8 (1st, 2nd, and 3rd strata):

$$P(k_{32}/H_{50}) = \frac{S_{k_{32}}}{S_{H_{50}}} = \frac{16}{103} = 0.15.$$

In compartment 51, on average, by age group, plantings belong to ripening stands (71-80 years), which was 90%. Fire hazard Class 1 – presence of plantings of age groups 2 and 3 (4th stratum):

$$P(k_{31}/H_{51}) = \frac{S_{k_{31}}}{S_{H_{51}}} = \frac{3}{80} = 0.03.$$

Fire hazard classes 2-4 – presence of plantings of age groups 4-8 (1st, 2nd, and 3rd strata):

$$P\ (k_{32}/H_{51}) = \frac{S_{k_{32}}}{S_{H_{51}}} = \frac{19.2}{80} = 0.24.$$

In compartment 60, on average, by age group, plantings belong to ripening stands (71-80 years), which was 90%. Fire hazard classes 2-4 – presence of plantings of age groups 4-8 (1st, 2nd, and 4th strata) and 9 (3th stratum):

$$P(k_{32}/H_{60}) = \frac{S_{k_{32}}}{S_{H_{60}}} = \frac{19.4}{50} = 0.38.$$

In compartment 61, on average, by age group, plantings belong to ripening stands (71-80 years), which was 90%. Fire hazard classes 2-4 – presence of plantings of age groups 4-8 (1st, 2nd, and 4th strata) and 9 (3rd statum):

$$P(k_{32}/H_{61}) = \frac{S_{k_{32}}}{S_{H_{60}}} = \frac{22.3}{40} = 0.55.$$

For compartment 50:

Fire hazard class 1 (4th stratum):

$$P(k_{41}/H_{50}) = P(k_{31}/H_{50}) = \frac{S_{k_{31}}}{S_{H_{50}}} = \frac{2}{103} = 0.01.$$

Fire hazard class 2 (2nd and 3rd strata):

$$P(k_{42}/H_{50}) = \frac{S_{k_{42}}}{S_{H_{50}}} = \frac{7+8.5}{103} = 0.15.$$

Fire hazard class 3 (1st stratum):

$$P(k_{43}/H_{50}) = \frac{S_{k_{42}}}{S_{H_{50}}} = \frac{0.5}{103} = 0.004.$$

For compartment 51:

Fire hazard class 1 (4th stratum):

$$P(k_{41}/H_{51}) = P(k_{31}/H_{51}) = \frac{S_{k_{31}}}{S_{H_{51}}} = \frac{3}{80} = 0.03.$$

Fire hazard class 2 (2nd and 3rd strata):

$$P(k_{42}/H_{51}) = \frac{S_{k_{42}}}{S_{H_{51}}} = \frac{9+9.5}{80} = 0.23.$$

Fire hazard class 3 (1st stratum):

$$P(k_{43}/H_{51}) = \frac{S_{k_{42}}}{S_{H_{51}}} = \frac{0.7}{80} = 0.008.$$

For compartment 60:

Fire hazard class 1 (4th stratum):

$$P(k_{41}/H_{60}) = P(k_{31}/H_{60}) = \frac{S_{k_{31}}}{S_{H_{60}}} = \frac{8}{50} = 0.16.$$

Fire hazard class 2 (2nd and 3rd strata):

$$P(k_{42}/H_{60}) = \frac{S_{k_{42}}}{S_{H_{60}}} = \frac{6+5}{50} = 0.22.$$

Fire hazard class 3 (1st stratum):

$$P(k_{43}/H_{60}) = \frac{S_{k_{42}}}{S_{H_{60}}} = \frac{0.4}{50} = 0.008.$$

For compartment 61:

Fire hazard class 1 (4th stratum):

$$P(k_{41}/H_{61}) = P(k_{31}/H_{61}) = \frac{S_{k_{31}}}{S_{H_{61}}} = \frac{9}{40} = 0.22.$$

Fire hazard class 2 (2^{nd} and 3^{rd} strata):

$$P(k_{42}/H_{61}) = \frac{S_{k_{42}}}{S_{H_{61}}} = \frac{5+8}{40} = 0.32.$$

Fire hazard class 3 (1^{st} stratum):

$$P(k_{43}/H_{61}) = \frac{S_{k_{42}}}{S_{H_{61}}} = \frac{0.3}{40} = 0.007.$$

The probability of fire occurrence in compartment 50 was calculated:

Fire hazard class 1:

$$\begin{gathered}P(H_{50})P(K_1/H_{50}) = P(H_{50})P(k_{11}/H_{50})\\ P(k_{21}/H_{50})P(k_{31}/H_{50})P(k_{41}/H_{50}) =\\ = 0.38 \ast 0.15 \ast 0.1 \ast 0.01 \ast 0.01 = 0.0000005.\end{gathered}$$

Fire hazard class 2:

$$\begin{gathered}P(H_{50})P(K_2/H_{50}) = P(H_{50})P(k_{11}/H_{50})\\ P(k_{21}/H_{50})P(k_{32}/H_{50})P(k_{42}/H_{50}) =\\ = 0.38 \ast 0.15 \ast 0.1 \ast 0.15 \ast 0.15 = 0.0001.\end{gathered}$$

Fire hazard class 3:

$$\begin{gathered}P(H_{50})P(K_3/H_{50}) = P(H_{50})P(k_{11}/H_{50})\\ P(k_{21}/H_{50})P(k_{32}/H_{50})P(k_{43}/H_{50}) =\\ = 0.38 \ast 0.15 \ast 0.1 \ast 0.15 \ast 0.004 = 0.000003.\end{gathered}$$

According to the calculation results, fire hazard class 2 is most probable for compartment 50. The probability of fire occurrence in compartment 51 was calculated:

Fire hazard class 1:

$$\begin{gathered}P(H_{51})P(K_1/H_{51}) = P(H_{51})P(k_{11}/H_{51})\\ P(k_{21}/H_{51})P(k_{31}/H_{51})P(k_{41}/H_{51}) =\\ = 0.29 \ast 0.19 \ast 0.27 \ast 0.03 \ast 0.03 = 0.00001.\end{gathered}$$

Fire hazard class 2:

$$\begin{gathered}P(H_{51})P(K_2/H_{51}) = P(H_{51})P(k_{11}/H_{51})\\ P(k_{21}/H_{51})P(k_{32}/H_{51})P(k_{42}/H_{51}) =\\ = 0.29 \ast 0.19 \ast 0.27 \ast 0.24 \ast 0.23 = 0.0008.\end{gathered}$$

Fire hazard class 3:

$$\begin{gathered}P(H_{51})P(K_3/H_{51}) = P(H_{51})P(k_{11}/H_{51})\\ P(k_{21}/H_{51})P(k_{32}/H_{51})P(k_{43}/H_{51}) =\\ = 0.29 \ast 0.19 \ast 0.27 \ast 0.24 \ast 0.008 = 0.00002.\end{gathered}$$

According to the calculation results, fire hazard class 2 is most likely for compartment 51. The probability of fire occurrence in compartment 60 was calculated:

Fire hazard class 1:

$$\begin{gathered}P(H_{60})P(K_1/H_{60}) = P(H_{60})P(k_{13}/H_{60})\\ P(k_{21}/H_{60})P(k_{32}/H_{60})P(k_{41}/H_{60}) =\\ = 0.18 \ast 0.38 \ast 0.22 \ast 0.38 \ast 0.16 = 0.0009.\end{gathered}$$

Fire hazard class 2:

$$\begin{gathered}P(H_{60})P(K_2/H_{60}) = P(H_{60})P(k_{13}/H_{60})\\ P(k_{21}/H_{60})P(k_{32}/H_{60})P(k^{42}/H_{60}) =\\ = 0.18 \ast 0.38 \ast 0.22 \ast 0.38 \ast 0.22 = 0.001.\end{gathered}$$

Fire hazard class 3:

$$\begin{gathered}P(H_{60})P(K_3/H_{60}) = P(H_{60})P(k_{13}/H_{60})\\ P(k_{21}/H_{60})P(k_{32}/H_{60})P(k_{43}/H_{60}) =\\ = 0.18 \ast 0.38 \ast 0.22 \ast 0.38 \ast 0.008 = 0.00004.\end{gathered}$$

According to the calculation results, fire hazard class 2 is most probable for compartment 60. The probability of fire occurrence in compartment 61 was calculated:

Fire hazard class 1:

$$\begin{gathered}P(H_{61})P(K_1/H_{61}) = P(H_{61})P(k_{13}/H_{61})\\ P(k_{21}/H_{61})P(k_{32}/H_{61})P(k_{41}/H_{61}) =\\ = 0.14 \ast 0.55 \ast 0.13 \ast 0.55 \ast 0.22 = 0.001.\end{gathered}$$

Fire hazard class 2:

$$\begin{gathered}P(H_{61})P(K_2/H_{61}) = P(H^{61})P(k_{13}/H_{61})\\ P(k_{21}/H_{61})P(k_{32}/H_{61})P(k_{42}/H_{61}) =\\ = 0.14 \ast 0.55 \ast 0.13 \ast 0.55 \ast 0.32 = 0.001.\end{gathered}$$

Fire hazard class 3:

$$P(H_{61})P(K_3/H_{61}) = P(H_{61})P(k_{13}/H_{61})$$
$$P(k_{21}/H_{61})P(k_{32}/H_{61})P(k_{43}/H_{61}) =$$
$$= 0.14*0.55*0.13*0.55*0.007 = 0.00003.$$

For compartment 61, fire hazard classes 1 and 2 are most likely. To determine the full probability of Class 2 fire in the forest, the K_2 event was selected:

$$P(K_2) = P(H_{50})P(K_2/H_{50}) + P(H_{51})$$
$$P(K_2/H_{51}) + P(H_{60})P(K_2/H_{60}) + P(H_{61})P(K_2/H_{61}) =$$
$$= 0.0001 + 0.0008 + 0.001 + 0.001 = 0.0029.$$

Using equation 3, the fire hazard of each compartment was estimated:

$$P(H_{50}/K_2) = \frac{P(H_{50})\,P(K_2/H_{50})}{P(K_2)} = \frac{0.0001}{0.0029} = 0.034.$$

$$P(H_{51}/K_2) = \frac{P(H_{51})\,P(K_2/H_{51})}{P(K_2)} = \frac{0.0008}{0.0029} = 0.27.$$

$$P(H_{60}/K_2) = \frac{P(H_{60})\,P(K_2/H_{60})}{P(K_2)} = \frac{0.001}{0.0029} = 0.34.$$

$$P(H_{61}/K_2) = \frac{P(H_{61})\,P(K_2/H_{61})}{P(K_2)} = \frac{0.001}{0.0029} = 0.34.$$

According to calculations, among compartments 50, 51, 60, 61, the most probable occurrence of a Class 2 fire is in compartments 60, 61, 51, and 50. The soils of the Bekhy forestry of the Korosten FHE are characterised by a neutral or slightly alkaline reaction. The results of the study of acid-base conditions in the studied soils exposed to fire are presented in Table 5.

Table 5. Indicators of average pH values in soils depending on the location in the terrain by burning areas and background area

Indicator			pH
Plot No. 1 affected by fire in 2022	Microhill	Lower horizon	7.55
		Upper horizon	7.38
	Microdepression	Lower horizon	7.35
		Upper horizon	7.35
Plot No. 2 affected by fire in 2023	Microhill	Lower horizon	7.35
		Upper horizon	7.3
	Microdepression	Lower horizon	7.55
		Upper horizon	7.35
Background areas	Microhill	Lower horizon	8.4
		Upper horizon	7.8
	Microdepression	Lower horizon	8.1
		Upper horizon	7.9

Source: compiled by the author

The measured pH values in the burning and background areas, mainly in the microrelief, showed the following results. In all soils, the pH values vary from the upper horizons to the lower ones from neutral to slightly alkaline. In the background plots, an increase in PH was observed at microhills and microdepressions of increase to the lower horizons. The lowest pH value is achieved in the upper horizons of soils of microhills and microdepressions (7.8 and 7.9, respectively). The highest pH value of background sites was observed in the lower soil horizons of 8.1 on microdepressions and 8.4 on microhills. At the site of fires in 2022, there was also an increase in the reaction of the environment to the lower soil horizons and a higher pH value at microhills. The highest indicator was observed in the lower horizons: on microhills – 7.55, on microdepressions – 7.35. The minimum values were reached in the upper horizons of microhills and microdepressions (7.38 and 7.35, respectively). In the areas of fires in 2023, the pH value differed in microrelief. Mostly on microdepressions, the pH is slightly higher in the upper part of the profile (7.35) than on microhills (7.3). The maximum pH value was reached in the lower soil horizon (Cca or Cs) and was 7.35 on microhills and 7.55 on microdepressions. Probably, the tendency to decrease the pH values in post-fire soils is explained by the fact that ash water-soluble compounds, penetrating into the soil, saturate the absorption complex with alkaline earth elements, compared to background areas.

The most important negative environmental effect of fires is the loss of organic matter by the ecosystem as a whole, including the loss of soil organic matter (Matkivskyi & Taras, 2024). With the help of studies, it was found that in soils exposed to thermal effects, a tendency to reduce the humus content in the 0-10 cm layer was observed. Fires have the greatest impact directly on the upper humus horizon of soils. The organic carbon content of the forests is decreasing from baseline to fire. In background areas, organic carbon values are higher than in areas of fires of different ages. The maximum organic carbon content in background soils ranged from 0.4% in microhills to 0.7% in microdepressions. The maximum value of organic carbon in background soils ranged from 0.4% in microhills and 0.7% in microdepressions. The 2022 fire site showed a slight increase in organic carbon in the upper humus horizon of soils, approximately 0.42% in microhills and 0.46% in microdepressions, compared to a less ancient fire. In the lower parts of the soil profile, the minimum organic carbon values of approximately 0.35% were achieved. In the 2023 fires, the organic carbon content was only 0.33% and 0.38% (microdepression and microhill, respectively), decreasing down the profile – 0.1% and 0.12% (microdepression and microhill, respectively).

Therefore, the decrease in organic carbon content is directly related to the activity of fires. Most likely, this is due to the thermal effect of fires on the top layer of soils, which led to the transformation and destruction of the humus horizon of soils.

Discussion

Analysing the results of the study, it can be concluded that the increase in the intensity of forest fires as a result of military operations negatively affected natural ecosystems. In particular, one of the most important problems is the destruction of the humus horizon of soils. The humus horizon is the top layer of soil rich in organic substances that ensure soil fertility and help to preserve moisture. As a result of the ecocide carried out by the aggressor state, in particular, the upper fertile layer of chernozem soils was destroyed. Over the past 100 years, Ukrainian soils have lost 30% of humus. Due to the impact of the war, the process of destruction accelerated. Fires burn organic material in the soil, such as plant remains, leaves, and roots (Shahini *et al.*, 2024). There is a decrease in the content of organic carbon, which is an important component of soil fertility.

It was found that the increase in the intensity of forest fires has had serious negative consequences for the ecosystem, in particular for forest soils, due to a decrease in the content of organic carbon in the soil (Skliar *et al.*, 2020). Similar question was considered by F. Niccoli *et al.* (2023). They found that the fires had significantly reduced the trees' ability to photosynthesise and absorb carbon dioxide (CO_2) due to defoliation and crown damage. Tree growth has decreased and water use has changed, which has affected the ability to store carbon and mitigate climate change. The results of the current study did not coincide with the conclusions of F. Niccoli *et al.* (2023), since they analysed the effect of organic carbon on soils on microhills and microdepressions of the lower and upper soil horizons.

It was noted that the organic carbon content of the background plots before the fires decreased, which is associated with the thermal impact of fires on the topsoil. The same problem was considered by Z. Cheng *et al*. (2023). They found that all three degrees of fire significantly increased microbial carbon concentrations in the soil, moisture content, and total nitrogen content, but they significantly reduced the available potassium content in the soil compared to unburned taiga forests. Indeed, fires do have a complex effect on soil properties, which was due to an increase in microbial carbon, since microorganisms can decompose carbon residues, in addition, potassium is an easily mobile element and can move quickly from the surface layer of the soil, especially during rains after a fire (Yanitskyi, 2024).

It has been found that the use of data from the Bayes' statistical mathematical model for fire assessment has resulted in a fairly accurate prediction of forest fires. A similar issue was studied by G. Alarcon-Aguirre *et al*. (2022). The researchers found that Sentinel-1's cross-polarisation optical image data has sufficient accuracy to detect and quantify fires. This statement should be accepted because Sentinel-1's cross-polarising optical images can indeed be a useful tool for detecting and assessing fires, especially when combined with satellite imagery data from the space remote sensing mission (Sentinel-2) and the Earth's remote area observation programme (Landsat).

According to the results of the study, it was shown that oak forests, in particular common oak stands, were the most fire-hazardous for compartments 60 and 61 of the Bekhy forestry of the Korosten FHE branch. A similar issue was studied by M. Heenatigala & G. Duh (2022). Based on the work of these researchers, it was established that certain types of forests, such as dry monsoon forests, were particularly vulnerable to forest fires and required priority restoration. Thus, both studies present different aspects of the study of forests and their fire hazard: determination of the most fire-prone composition of forest stands in this study and analysis of vulnerability to fires by M. Heenatigala & G. Duh.

Soils that were exposed to fire in 2022 and 2023 showed higher pH values than in the background areas of the upper soil horizons on microhills and microdepressions. The dynamics of these indicators were considered by E. Nandakumar *et al*. (2024), where specified, that as a result of a forest fire, a higher pH level of the soil was found on the burnt surface of the soil than on the unburned land area. Similar conclusions were obtained in the study, according to which it was revealed that in the background areas the lowest pH value was reached in the upper horizons of soils of microhills of 7.8 and microdepressions of 7.9, but the highest pH value was observed in the lower horizons of soils on microdepressions – 8.1 and on microhills – 8.4. In the areas of fires in 2022, the lowest pH values were established in the upper horizons of microhills at 7.38 and microdepressions – 7.35, and in 2023, the minimum pH values were reached in the upper horizon of soils, which was 7.35 on microdepressions, 7.3 on microhills.

According to statistics on taxation indicators of compartments, it was revealed that the most vulnerable plant to fires for compartments 50 and 51 was Scots pine, but for compartments 60 and 61 such a plant was common oak. A similar issue was considered by K. Raj *et al*. (2023). Based on the results obtained by them, it was noted that the use of the statistical method of the Canadian fire weather index and the Australian fire hazard index to assess vegetation vulnerability to fire has contributed to the creation of effective and accurate models of forest fires based on the use of stochastic and mathematical methods. The conclusions by K. Raj *et al*. indicate that stochastic and mathematical methods allow developing predictive models that consider random factors and natural changes, such as changes in weather and climate.

It was demonstrated that the mathematical model for predicting the risk of forest fires had high accuracy, since modern mathematical models can work with large amounts of data, which increases the accuracy of forecasts. A similar study was conducted by Y. Li *et al*. (2020). According to the researchers, the Random Forest model showed the highest accuracy – 89.2%, compared to such models as an artificial neural network, a network of radial basis functions, and a support vector machine, which indicated its effectiveness in predicting the likely occurrence of forest fires. The authors agree with this statement, since the Random Forest model is an effective machine learning method for various classification and regression tasks due to its ability to process a large number of input variables, reduce the risk of overtraining, and provide high accuracy of forecasts.

It was recorded that the most likely occurrence of a Class 2 fire was in compartments 60 and 61, the fire hazard coefficient of which was 0.34. Research on a similar issue was carried out by R. Bagherabadi *et al*. (2022). The map of high-risk areas for forest fires showed that the largest part of the territory covered by forest fires included areas with medium risk, which amounted to 33.43%. The results obtained in the presented study differ from the conclusions drawn in the paper by R. Bagherabadi *et al*. (2022), which may be due to differences in the research methods they used, such as the geographic information systems method in the analysed study and the Bayes' statistical mathematical model method in the present study.

The mathematical model for predicting the risk of forest fires is highly effective, since it considered the probability of fire based on various factors, such as the composition of plantings, stand density, the age of forest stands, and the type of forest conditions. The issue under discussion was investigated by D.D. Perrakis *et al*. (2023). Based on the results of their study, it was noted, that the updated models based on a systematic approach to fire initiation and propagation were more efficient than fixed-fuel models. The authors of this study agree with this statement, since the improved fire probability models considered variables of the fire environment, such as wind speed, destruction of fuel layers, humidity of the litter, and consumption of the amount of fuel used by the fire on the surface.

In Zhytomyr Oblast, in 2023, 10 fires were registered on the territory of seven forest districts, but compared to 2022, the area covered by fires has become three times smaller, which is conditioned by active measures to restore forest ecosystems, including planting trees less susceptible to fires. The study of a similar issue was carried out by S. Connor *et al*. (2021). Their research found that prolonged drought caused the death of pine plantations, but also a decrease in the number of fires, which led to the restoration of the coastal pine forest. This statement can be agreed with, as coastal pine forests do have a high capacity for natural regeneration, provided there are no significant negative factors such as fires.

Using statistical data, it is possible to identify the fire hazard of each quarter separately throughout the entire territory of Bekhy forestry. Such an issue was studied by M. Ibraheem *et al*. (2024). It was revealed that the Forest Defender Fusion early detection system has achieved high efficiency in identifying and monitoring forest fires with an accuracy of 99.86%, significantly exceeding the performance of other existing models that use input red, green, blue, and infrared image analysis. We should agree with the results of this study, since the Forest Defender Fusion early detection system really demonstrated efficiency in using advanced technologies for monitoring and detecting fires, which allowed for timely response and minimising environmental damage.

Inventory reduction detected organic carbon at the sites of fires in 2023. A similar issue was studied by H. Bargali *et al*. (2024). Based on the results of their work, it can be stated that the frequent occurrence of fires has led to a significant reduction in organic carbon stocks, especially in high-frequency fire classes. When plant biomass is burned, carbon is released into the atmosphere as carbon dioxide (CO_2), which leads to a decrease in total organic carbon reserves in ecosystems (Babak *et al*., 2021).

Content of organic carbon decreased down the profile by 0.1% on microdepressions and 0.12% on microhills. A similar problem has been investigated by B.M. Rodríguez-Cardona *et al*. (2020). It was shown that forest fires increased nitrate concentrations over a ten-year period, which led to a decrease in dissolved organic carbon and nitrogen concentrations over a fifty-year period. Agreeing with the statement, it should be noted that the opinion of B.M. Rodríguez-Cardona *et al*. is correct, as the burning of plant mass releases nitrates that can be leached into the soil, increasing the concentration of nitrates in the long term.

An increase in organic carbon concentration of approximately 0.42% was detected at the 2022 burn site, with a 0.46% increase in microhills, compared to 0.42% in microdepressions. A similar issue has been investigated by I. Megremi *et al*. (2024). They presented the results, according to which an increase in the concentration of organic carbon in the areas affected by the fire indicated incomplete combustion of vegetation. Similar conclusions were obtained in this study, since the presented results also indicate the presence of increased carbon content in the upper humus horizon of soils.

The presented study reported that the pH of the soil from 7.9 to 7.55 was in a slightly alkaline range, which contributed to a good growth of many types of tree stands. A similar issue was studied by S.J. Rance *et al*. (2020). The researchers found that phosphorus increased the pH of the soil and stimulated tree growth, while nitrogen and sulphur lowered the pH. This formulation of the researchers' conclusions should be agreed with, since phosphorus can actually affect the pH of the soil, increasing the PH concentration, since phosphate fertilisers have alkaline properties. At the same time, nitrogen and sulphur can lower the pH of the soil due to the generation of acidic compounds during their decomposition (Shahini *et al*., 2022).

After the fire, the highest pH values were observed in the lower horizons, while organic carbon was lost most in the upper horizon after the fire. This issue was also studied by T. Whitman *et al*. (2022). According to the researchers, five years after the fire, the plant community, pH, and total carbon did not acquire the same state as before the fire, while bacterial communities recovered throughout the area covered by the fire. According to T. Whitman *et al*. (2022), since bacteria have a high potential to adapt and multiply rapidly in new conditions, even with changes in pH, humidity, and organic matter levels.

The decrease in organic carbon content is directly related to the thermal effect of fires on the topsoil. This topic was investigated by J. Adkins & J.R. Miesel (2021). It is shown that at high soil temperatures (up to 200°C), the soil's ability to absorb carbon decreased. Similar conclusions were obtained in the presented study, since the results showed a tendency to reduce the carbon content, which led to the destruction of the humus horizon of soils.

A decrease in organic carbon content was detected at the 2023 burn sites. A similar topic was studied by A. Girona-García *et al*. (2024). It was noted that organic carbon erosion can absorb up to 13% of carbon emissions within one year of a fire. The findings of the present study coincided with the conclusions of A. Girona-García *et al*. (2024), since they monitored the organic carbon content in soils before and after fires, and also found a decrease in the organic carbon content after fires.

In the background areas, there was a higher level of organic carbon compared to the areas by fires. A similar topic was studied by S.C. Panico *et al*. (2022). It was shown that in the post-fire period, there was a significant increase in the level of organic substances and the ratio of carbon to nitrogen (C/N). According to S.C. Panico *et al*. (2022), an increase in organic matter and the C/N ratio may indicate the destruction of organic matter and its carbon-nitrogen composition as a result of a fire.

In 2022, all organic carbon reserves in the soil increased linearly over time after the fire. The same topic was considered by B. Andrieux *et al*. (2020). Based on the findings, it was shown that soil organic carbon stocks increased at 0.02 and 0.12 MgC/ha^{-1} year^{-1} after the fire. It is worth agreeing with B. Andrieux *et al*. (2022), since fire can alter the structure and composition of the soil, which can contribute to faster decomposition of organic materials and, consequently, the accumulation of organic carbon.

In this section, a literature review was conducted and studies on the impact of forest fires on the ecosystem, in particular on changes in soil and photosynthesis of trees, were considered. A study was conducted on the impact of forest fires on soil properties and the vulnerability of different types of forests to forest fires, including dry monsoon forests.

Conclusions

The results of the study of the impact of fires on soil properties showed that as a result of fires, there was a tendency to decrease the pH values in soils of the post-fire period, which was explained by the fact that ash water-soluble compounds, when penetrating into the soil, can saturate the absorbing complex with alkaline earth elements. In the background plots, the pH level increased to the lower horizons, with the maximum value in the lower part of the profile (8.1 for microdepressions and 8.4 for microhills). In the soils covered by the fire, a decrease in carbon was observed, which is associated with the destruction of the upper horizon due to thermal exposure. The maximum organic carbon content was found in background areas (0.4% in microhills and 0.7% in microdepressions).

In the Zhytomyr Oblast, in 2022, 5 fires were recorded on the territory of three forest districts, covering an area of 12.1 ha, and in 2023 – 10 fires on the territory of seven forest districts, covering an area of 3.03 ha. Using the model used, the probabilities of fires occurring in each quarter were determined, and factors influencing their occurrence were considered, such as the composition of forest stands, stand density, the age of forest stands, and the type of forest conditions. For compartments 50, 51, 60, and 61, the total area of which was 270.4 ha, the probability of fire was determined. The highest probability was for compartment 50 (0.38), and the lowest for compartment 61 (0.14). As a result of the study, common oak stands were the most fire-prone for compartments 60 and 61. Pine stands were the most dangerous for compartments 50 and 51.

In the review of studies of the territories covered by forest fires in the Zhytomyr Oblast, it is necessary to note the unavailability of some data on the state of soils for analysis. The study did not consider the impact of fires on soil biological components, such as microorganisms and plant root systems, which can also affect ecosystem recovery. Areas of further research may include the introduction of regular monitoring of changes in the physical and chemical properties of soils in areas covered by fires, to assess the long-term consequences of fires, improving models for predicting the probability of fires, considering new data on the state of soils and afforestation, and climate change.

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Conflict of Interest

None.

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Аналіз та прогнозування масштабів та наслідків впливу лісових пожеж на екосистеми України

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Анотація. Лісові пожежі є однією з найбільш значущих екологічних проблем, які мають суттєвий вплив на біорізноманіття та кліматичні умови. Метою дослідження було вивчення впливу військових дій на ґрунтовий покрив у зоні Бехівського лісництва, який порушений пожежею. По результатам дослідження виявлено, що за період 2022-2023 років на території філії “Коростенське лісомисливське господарство” державного підприємства “Ліси України” зафіксовано 15 лісових пожеж, при цьому загальна охоплена пожежами площа склала 15,13 гектарів. Загалом, кількість пожеж збільшилася від 5 до 10, але загальна площа, охоплена пожежами, зменшилася з 12,1 до 3,03 гектарів. На ділянці пожеж у 2022 році спостерігалося підвищення рівня pH до нижніх горизонтів, з найбільшим значенням на мікропідвищеннях (7,55) та на мікропониженнях (7,35). Відмічено невелике збільшення вмісту органічного вуглецю у верхній гумусовому горизонті ґрунтів (0,42 % на мікропідвищеннях і 0,46 % на мікропониженнях). Бехівське лісництво зазнало великої лісової пожежі в травні 2023 року, яка охопила площу 1,2 гектарів. Була проведена оцінка пожежонебезпечності кожного кварталу окремо. У 50 та 51 кварталі сосна звичайна виявилася найбільш пожежонебезпечним видом насаджень. Ділянка пожеж у 2023 році також показала підвищення pH у нижніх горизонтах, з найвищими значеннями на мікропідвищеннях (7,35) та на мікропониженнях (7,55). Ділянка пожеж у 2023 році демонструвала зменшення вмісту органічного вуглецю в порівнянні з фоновими ділянками, з мінімальними значеннями в нижніх частинах ґрунтового профілю (0,33 % на мікропониженнях і 0,38 % на мікропідвищеннях). Результати дослідження можуть бути використані з метою розробки та впровадження екологічних заходів та програм, спрямованих на відновлення пошкоджених пожежею лісів

Ключові слова: математичне моделювання; імовірнісні оцінки; теорема Байєса; вуглець; ґрунтовий профіль; фонові ділянки