JEE Journal of Ecological Engineering

Journal of Ecological Engineering, 2025, 26(3), 350–364
https://doi.org/10.12911/22998993/199472
ISSN 2299–8993, License CC-BY 4.0

Received: 2024.11.23
Accepted: 2025.01.17
Published: 2025.02.01

Impact of forest fire on the heavy metal content in the soil cover of the Amankaragay pine forest, Kostanay Region

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ABSTRACT

The soils of the Amankaragay Pine Forest in the Kostanay Region of the Republic of Kazakhstan, which experienced a large forest fire in September 2022, were studied. Research on the impact of forest fires on the soil cover of pine forests is conducted worldwide, but there is a lack of studies on island-like pine forests growing on eolian sand masses in dry steppe zones. In this study, we analyzed the heavy metal content one year after the intense forest fire. Soil samples were collected from both control plots and areas affected by the fire. Our results showed significant changes in soil characteristics in the burned areas compared to the control sites. The content of heavy metals such as aluminum, cadmium, chromium, iron, manganese, lead, vanadium, zinc, and mercury was examined. Heavy metal content was determined using the inductively coupled plasma atomic emission spectroscopy method. The obtained data on the content and accumulation of heavy metals reflect the distribution patterns in both control and fire-affected key sites. Understanding changes in heavy metal content in the soil cover is essential for planning forest stand restoration efforts after fires. The results of this study may serve as a basis for developing forest management strategies post-fire.

Keywords: forest, soil, soil property transformation, soil chemical composition, heavy metals, post-fire forest recovery.

INTRODUCTION

In recent years, the increased frequency and severity of forest fires has also been associated with climate change to some extent [Williams et al., 2019]. Forest fires are an almost constant threat to life, an impact that cannot be reduced but they are also a threat to the environment and can be seen in the form of climate change [Burke et al., 2021; Ertugrul et al., 2021]. Thus, forest fire and climate change is intertwined concepts. Climate change [Goss et al., 2020] and the wildland-urban interfaces (WUIs) [Radeloff et al., 2018] have increased the frequency and devastating impacts of wildfires. The effects of global climate change have led to a rise in temperature and a fall in precipitation, shaping a prolonged dry and warm period that favours the ignition and spread of wildfires [Radeloff et al., 2018].

Droughts, heat waves, climate variability and regional weather patterns can increase the risk and alter the behaviour of forest fires [Turco et al., 2018].

Further, the forest fire incidences remain strongly connected to the annual climate variability [Drobyshev et al., 2021], topography and composition of forests [Broncano and Retana, 2004]. Forest fire is one of the unpredictable natural calamities and has caused tremendous damage to humans, animals and nature, as well as extinction and economic loss to the inhabitants [Mateus and Gaspar, 2018; Kizer, 2020; Singh and Suresh, 2021].

Forest fires affect the physical-chemical and biological properties of soils. The transformation of soil properties depends on the intensity and duration of the fire. Severe forest fires have a negative impact on soils. They contribute to soil contamination with heavy metals, leading to ecosystem degradation. A forest fire transforms the entire landscape. Fire is one of the most important causes of impacts in ecosystems. Fire can lead to important changes in the properties of forest soils [Neill et al., 2007], which support critical processes such as hydrologic and biogeochemical cycling [Neary et al., 1999].

A forest fire can change the soil properties including soil texture, soil colour, soil water content, bulk density, CEC, hydraulic conductivity, porosity, pH, EC, macronutrients, micronutrients and microbes, which are the effects of forest fires on soil properties [Certini, 2005].

Degradation of the biological, chemical, and physical properties of forest soils reduce its capacity to function fully, with such effects either temporary or permanent. Key drivers of soil degradation in forest ecosystems are deforestation, fires, erosion, and soil contamination [Ghazoul et al., 2015; Silverio et al., 2019].

Forest burning is accompanied, on one hand, by the release of heavy metals and artificial radionuclides into the atmosphere, and on the other hand, by the passive accumulation of certain metals in burn sites. The behavior of chemical elements is influenced by their geochemical characteristics, distribution patterns in forest fuel materials, fire type, weather conditions, and other factors [Shcherbov, 2011; Shcherbov et al., 2015; Shcherbov, 2010].

There is greater pyrogenic vulnerability in soils under pine forest types compared to soils under birch or mixed birch-pine forests. In burn sites beneath dead pine stands, transformations in the morphological and chemical properties of soils have been observed [Shakhmatova, 2008].

Objects and methods of research

The objects of research are soils in Amankaragai pine forest (Figure 1).

Kostanay region is located in the northern part of the Republic of Kazakhstan. The natural and climatic features of the study area are determined by its inland position, far from the oceans, resulting in a sharply continental climate with hot, dry summers and cold winters.

To the north and northwest, Kostanay region borders the Russian Federation; to the west and southwest, it borders Aktobe region; to the east, it borders North Kazakhstan and Akmolinsk regions; and to the southeast, it borders Karaganda region of Kazakhstan.

The Amankaragay pine forest is located in the southern part of the Kostanay (Northern Turgai) plain and is the largest island-like forest massif

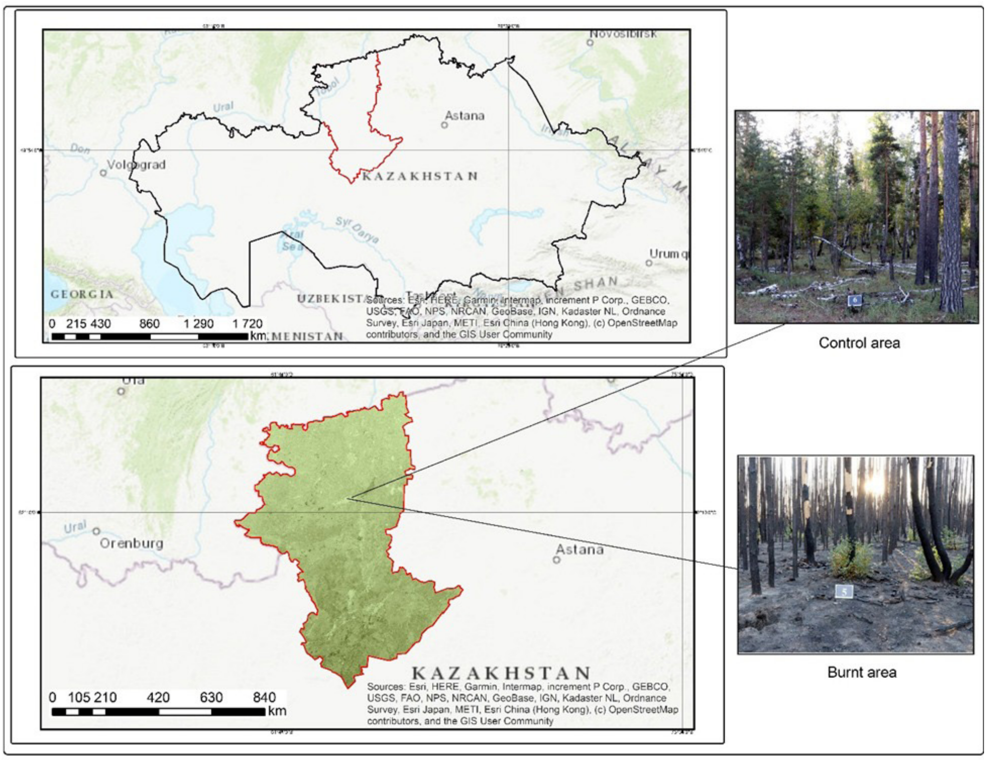

Figure 1. Map of the study area

in the Kostanay region. The soil-forming rocks in the Amankaragay pine forest are white sands, loams, and clay loams. The origin of the landscape in the studied region is associated with alluvial and subsequent eolian processes. Eolian landforms alternate with gentle sand ridges and lower, gently sloping hillocks with small depressions between them. In some areas, particularly in the lower parts along mounds and ridges, they resemble floodplain meadows, inundated by spring meltwaters and occasionally waterlogged.

The study area belongs to the subzone of chestnut and brown soils. In enclosed depressions, under pine islands, solonchaks, meadow, and meadow-chestnut soils develop. The following soil types are identified in the study area: soddy-pine; brown forest, secondary soddy; gray forest; dark gray solonetzic; gleied solonchaks; solonetzic swampy soils. The studied territory is part of the steppe zone, within the subzone of arid steppes. The region of grass-covered pine forests in the ancient Abugo-Tobol depression of ancient runoff consists of two sandy, northeastwardly elongated, disconnected massifs within the northern half of the steppe landscape zone. The main forest-forming species is Scots pine (*Pinus sylvestris*).

One of the factors contributing to the forest fire in 2022 in the Amankaragay pine forest of Kostanay region was the dry, hot weather with no precipitation. Warming trends and recurring droughts increase the likelihood of forest wildfires occurring worldwide [Dezzeo and Chacyn, 2005; Viegas, 2006; Castroet al., 2012].

Forest fires from 2001 to 2019: According to forest fire zoning, the area of the forest institution is classified as part of the Amankaragay forest fire district, with a fire hazard period lasting 208 days. Since 2001, 88 cases of forest fires have been registered in the study area, covering a total of 5,249.9 hectares, including 5,010.7 hectares of forested land, represented by plantations and forest cultures. The main causes of surface forest fires were: thunderstorms (53%), careless handling of fire (by the population) (22%), unidentified causes (16%), arson (7%), and fires from steppe fires and electrical wiring short circuits (2%). A major forest fire occurred in September 2022 in the Amankaragay forest, covering a vast area – such a fire had not been recorded in the region for the past 30 years.

The subject of the study was the analysis of heavy metal content in soils under post-pyrogenic conditions in the Amankaragay pine forest. Studying the content of heavy metals is necessary due to the potential negative impact on the natural regeneration of pine, as toxic concentrations of heavy metals can cause significant harm to young pine seedlings. Forest fires lead to changes in the geochemical properties of soils not only in the burned areas but also in adjacent territories. Changes in the geochemical background of burned soils inevitably affect the vegetation cover. Therefore, studying the chemical composition of plants in burned areas is of significant ecological importance.

Without studying post-fire changes in the soil cover, it is impossible to understand the recovery dynamics of forest ecosystem components and to develop predictions of their condition under different fire impacts.

The objective of this study is to assess the impact of forest fires on the redistribution of elements. To achieve this, the behavior of heavy metals – aluminum, cadmium, chromium, iron, manganese, lead, vanadium, zinc, and mercury – during surface forest fires was examined by comparing their concentrations in background and burned soils. Many of these heavy metals are among the highest-priority environmental pollutants and are toxic at high concentrations. This study does not aim to investigate the mobile forms of heavy metals.

The process of natural pine regeneration in the Amankaragai forest after the fire is proceeding unevenly. The prolonged drought in 2022, which contributed to the rapid spread of the fire, also hindered natural regeneration in the forest over the past year. The summer of 2023 was similarly dry, with continuous rains only starting at the end of the summer, which facilitated the germination of Scots pine seedlings. The seed material that did not sprout in the spring began to germinate in large numbers in the fall, primarily in the lowlands where moisture remains longer.

Field studies were conducted during the summer of 2023 and 2024. Seven key sites were identified in the study area. Table 1.

Samples were collected from the root zone, suitable for the germination and young regeneration of pine, in the soil layer. The soil samples consisted of products from the combustion of the forest litter or its remnants, as well as the upper soil layer. Samples were taken from both control sites and the burned areas.

The control key plots and the plots affected by the forest fire are similar in terms of soil

Table 1. Key sites in the Amankaragay pine forest

№	Name of the forest enterprise	Name of the forestry unit	Coordinates	Forest compartment number
1	Semiozernoye	Kalininskoye	52°25´14.70´´ N 64°10´11.59´´ E	107
2	Basaman	Zapadnoye	52°25´52.55´´ N 63°38´48.83´´ E	3
3	Semiozernoye	Novonezhina	52°30´21.46´´ N 64°4´16.48´´ E	20
4	Semiozernoye	Novonezhina	52°30´47.54´´ N 64°5´26.08´´ E	9
5	Semiozernoye	Novonezhina	52°30´38.52´´ N 64°3´21.89´´ E	7
6	Semiozernoye	Novonezhina	52°30´24.12´´ N 64°4´0.61´´ E	7
7	Semiozernoye	Kalininskoye	52°27´9.06´´ N 64°5´3.56´´ E	54

composition and vegetation. Soil samples were collected in the Semiozernoe and Basaman forestry institutions. The area of steppe pine forests consists of two sandy, northeast-oriented, isolated massifs within the northern half of the steppe landscape zone. The primary forest-forming species is Scots pine, with birch and aspen also present, forming both pure and mixed stands.

The analysis of heavy metal content was carried out in the certified laboratory of "Azimut Geology" LLP and "Ekonus" LLP in the city of Karaganda. The heavy metal content in the soils was determined using the atomic emission spectroscopy method with inductively coupled plasma. MVT KZ.07.00.01378-2016.

Statistical analysis of the data obtained during the study was carried out using the Statistica software. The following statistical indicators were used in data processing: n – the number of samples; $\bar{x} \pm S\bar{x}$ – arithmetic mean and its error; (mg/kg); C_V – coefficient of variation (%); lim – limits of fluctuation (mg/kg); σ – standard deviation (mg/kg);

The results and their discussion

We studied 7 key sites, among which the most affected by the forest fire were key sites No. 5 and No. 7, where a crown fire of medium intensity occurred. In key site No. 5, in the section 5 of compartment 7 of the Novonezhinskoye forestry, medium-aged forest plantations (44 years old) were present, while in key site No. 7, in section 27 of compartment 54 of the Kalininskoye forestry, medium-aged natural plantations (53 years old) were found. Both sites share similar characteristics: high stocking (0.7–0.8), bonitet (II), and stand volume per hectare (190 m^3). The vegetation in these sites was completely burned with no possibility of regrowth or recovery, and the height of the burn mark exceeds 12 meters.

On the burned areas of Scots pine and several other coniferous species, natural regeneration of hanging birch (Betula pendula) is the first to appear. Figure 2. Due to its biological characteristic of fast growth, deciduous species, particularly birch, surpass the growth of the main species, Scots pine, during the first growing season.

The average bonitet of all studied key sites is assessed by us as III, which is related to the untimely conduct of thinning operations, leading to a decrease in the annual growth of the stands. The sanitary condition of the stands in key sites No. 1, No. 5, and No. 7 is unsatisfactory compared to the other sites. The soils of the studied key sites are not compacted and are favorable for growth. In key site No. 1, a compacted crust was observed in the surface soil layer.

Uneven natural regeneration of Scots pine is observed after the fire. The germination of pine seeds is predominantly associated with more humid lowlands and loosened areas of soil.

Fire in the forest not only destroys the ground cover but also alters the physical properties of the soil. Specifically, soil density significantly increases, while its moisture retention and permeability decrease. Changes in the physical and chemical properties of the soil cover in the burned areas are associated with the different behavior of individual elements: some are released into the atmosphere, while others accumulate in the burned areas.

Figure 2. Key site No. 5

The impact of a ground fire on soil morphology, humus content, pH levels, hydrolytic acidity, and cation exchange capacity was studied. The mobility of heavy metals is influenced by factors such as the decomposition of organic matter, changes in pH, and the redox potential or composition of the soil due to natural processes of weathering or fire-related alterations.

The studied soils are characterized by low humus content, ranging from 1.4% to 4.5% (with an average of 2.3%), and the soil pH is close to slightly acidic, ranging from 5.9 to 7.2 (with an average of 6.3). The hydrolytic acidity varies from 1.26 to 6.53 mmol/equiv, with an average of 3.96 mg/equiv. The cation exchange capacity is moderate, ranging from 17 to 35 (with an average of 25). The forest fire did not have a significant impact on the cation exchange capacity (see Table 2).

The minimum humus content was found in the topsoil of key site #5 on the fire-affected areas (see Figure 2). The slight presence of organic matter can be attributed to mineralization resulting from the fire that occurred.

Soil profiles established in key sites #5 and #6 showed a decrease in hydrolytic acidity in the 10–30 cm layer. This was due to an increase in the content of water-soluble alkaline compounds leached from the ash remaining after the forest litter burned.

The study examined the content of heavy metals in the soils: aluminum, cadmium, chromium, iron, manganese, lead, vanadium, zinc, and mercury. Many of these heavy metals are among the most prioritized environmental pollutants and are ecotoxic at high concentrations. The increase of heavy metals in landscape components can change due to the impact of fires.

An important aspect of environmental protection and one of the ecological characteristics of heavy metals is understanding their normal (background) content in soils and the parameters of their potential anthropogenic changes. This knowledge enables the monitoring of soil cover conditions, determination of pollution rates, and the extent of heavy metal contamination [Maistreko et al., 1996]. Background levels of heavy metals in soil are based on average statistical data on the content

Table 2. Variational-statistical indicators in the soils of the Amankaragai forest, for 2024, mg/kg

Parameters	X±Sx	lim	σ	C_V, %
Hydrolytic acidity	3.96±0.66	1.26–6.53	1.61	40.74
Cation exchange capacity	25±2.04	17–35	5	20
hydrogen ion concentration	6.38±0.15	5.9–7.2	0.38	5.92
Humus	2.37±0.37	1.4–4.5	0.77	32.39

of these elements in various soil types, excluding data from anthropogenically contaminated soils. To determine the background (control) content of heavy metals, we collected samples from similar areas with unburned soils, unaffected by forest fires. An important aspect of environmental protection and one of the ecological characteristics of heavy metals is understanding their normal (background) content in soils and the parameters of their potential anthropogenic changes. This knowledge enables the monitoring of soil cover conditions, determination of pollution rates, and the extent of heavy metal contamination [Maistreko et al., 1996]. Background levels of heavy metals in soil are based on average statistical data on the content of these elements in various soil types, excluding data from anthropogenically contaminated soils. To determine the background (control) content of heavy metals, we collected samples from similar areas with unburned soils, unaffected by forest fires. Background levels of heavy metals in soil are based on average statistical data on the content of these elements in various soil types, excluding data from anthropogenically contaminated soils. To determine the background (control) content of heavy metals, we collected samples from similar areas with unburned soils, unaffected by forest fires. An important aspect of environmental protection and one of the ecological characteristics of heavy metals is understanding their normal (background) content in soils and the parameters of their potential anthropogenic changes. This knowledge enables the monitoring of soil cover conditions, determination of pollution rates, and the extent of heavy metal contamination [Maistreko et al., 1996]. Background levels of heavy metals in soil are based on average statistical data on the content of these elements in various soil types, excluding data from anthropogenically contaminated soils. To determine the background (control) content of heavy metals, we collected samples from similar areas with unburned soils, unaffected by forest fires.

Aluminium (Al) is the third most common and ubiquitous element in the world. It is naturally found in air, soil, and water [Barabasz et al., 2002]. Aluminum can have a negative impact on plants. Free aluminum ions in toxic concentrations cause significant damage to cultivated plants. Aluminum is considered the primary toxic element when growing plants on acidic soils [Amosova and Synzynys, 2005]. Therefore, the study of aluminum content in forest soils after a fire is important for understanding the potential for the natural restoration of the forest stand.

In 2023, the aluminum content in the soils of the Amankara gay forest ranges from 14.558 to 78.938 mg/kg, with the average content being 27.837 mg/kg (Table 3). To determine the variability of aluminum content across key sites, the coefficient of variation was used, which indicates the degree of variability of the parameter. The data showed significant variability in the spatial distribution of aluminum, with a coefficient of variation of 59.29%. The maximum concentration of total aluminum content in the upper soil horizon, 78,938 mg/kg, was found in key site No. 1, which is 11 times higher than the Clarke value for aluminum in Earth's soils, according to Vinogradov [Vinogradov, 1957]. The minimum concentrations are characteristic of background key sites that were not affected by the forest fire: key site No. 3 with an aluminum content of 15,143 mg/kg and key site No. 6 with 14,558 mg/kg.

Table 3. Variational-statistical indicators of heavy metals in soils of the Amankaragay forest, 2023 (mg/kg)

Parameters	X±Sx	lim	σ	C_{V}, %
Al	27837±6238.45	14558–78938	16505.39	59.29
Cd	0.11±0.02	0.06–0.23	0.04	36.84
Cr	45.87±6.28	29.3–97.2	16.64	36.28
Fe	20427.86±2304.95	10533–39364	6108.11	29.90
Mn	750±55.53	465–1363	147.17	19.62
Pb	12.04±1.20	7.09–20.33	1.20	26.37
Va	69.58±16.04	42.8–154.7	42.5	61.08
Zn	55.78±7.92	18.1–102.6	21	37.65
Mg	4287.29±1123.21	1907–9960	2976.5	69.43
Na	3293.14±592.64	2526–5978	1570.5	47.69
Hg	0.0111±0.0016	0.0033–0.0220	0.0044	39.24

In 2024, the aluminum content in the soils ranged from 12,195.06 to 16,661.43 mg/kg, with an average content of 14,231.13 mg/kg, which is lower compared to 2023. (Table 5). The maximum aluminum content was found in key site No. 1 at 14.999 mg/kg and in key site No. 4 at 15,977.03 mg/kg. The minimum concentrations were found in background key sites that were not affected by the forest fire: key sites No. 3 and No. 5, with aluminum contents of 12,370.82 mg/kg and 10,667.36 mg/kg, respectively. The studies on the dynamics of aluminum content showed that, in 2024, there was a decrease in aluminum levels (Figure 3).

Key plot No. 1, located in section 1 of quarter 107 of the Kalininsky forestry of the Semiozernoye forest management institution, was selected as one of the key areas due to the fact that, after the fire, a large number of trees were felled and broken at a height of 2.5–3.5 meters, scattered in two opposite directions. Figure 4. Increased levels of aluminum (78.938 mg/kg), cadmium (0.23 mg/kg), chromium (97.2 mg/kg), iron (39.364 mg/kg), vanadium (154.7 mg/kg), and zinc (88.7 mg/kg) were found in the upper soil horizon of Key Plot No. 1. Research conducted in 2024 showed a decrease in the levels of aluminum, chromium, iron, manganese, vanadium, and zinc compared to the 2023 levels, while there was a slight increase in lead and mercury content. Table 4.

The increased levels of certain heavy metals are not associated with other environmental inputs, such as atmospheric deposition or runoff from

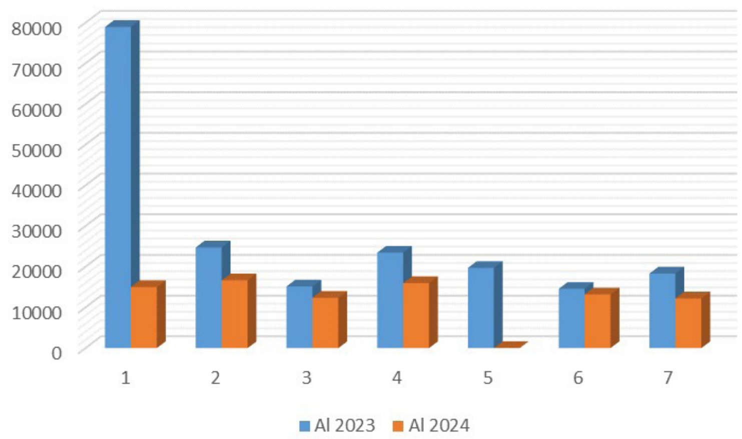

Figure 3. Aluminum content in the soil cover of the Amankaragai forest for the years 2023–2024. The vertical axis represents the content of heavy metals in mg/kg, and the horizontal axis represents the numbers of the key sites

Figure 4. Key plot No. 1

Table 4. Variational-statistical indicators of heavy metals for key plot 1, 2023–2024, in mg/kg

Parameters	2023	2024
Al	78938	15000
Cd	0.23	0.19
Cr	97.2	61.24
Fe	39364	21814.70
Mn	654	451.1
Pb	12	22.44
Va	154.7	27.5
Zn	88.7	49.67
Hg	0.033	0.062

surrounding areas. Annual studies conducted by the Kostanay regional branch of the RSE "Kazhydromet" under the Ministry of Ecology and Natural Resources of the Republic of Kazakhstan have shown that the data on heavy metal concentrations in the soils of the studied area, presented in the Environmental Status Bulletin of Kostanay Region for 2022–2024, were within permissible limits. In 2022, at the phenological site of the Auliekol agrometeorological post, concentrations of cadmium, lead, zinc, copper, and chromium ranged between 0.10 and 9.57 mg/kg, remaining within permissible limits. In 2023, concentrations of cadmium, lead, zinc, copper, and chromium ranged between 0.09 and 8.14 mg/kg, also within permissible limits. In the first half of 2024, at the phenological site of the Auliekol agrometeorological post, concentrations of cadmium, lead, zinc, copper, and chromium ranged between 0.1 and 7.40 mg/kg, remaining within permissible limits.

Cadmium (Cd) is among the metal contamination, and is considered as a major environmental concern to the agricultural system as its residence time in soil is over thousands years [di Toppi and Gabbrielli, 1999].

The average cadmium content in 2023 was 0.11 mg/kg, with a range of limits from 0.06 to 0.23 mg/kg (Table 3). The minimum cadmium content of 0.06 and 0.07 mg/kg was characteristic of key plots No. 3 and No. 6, respectively, which are considered background plots and were not exposed to fire. The maximum concentration of cadmium in the surface soil layer was found in key plot No. 1, with a cadmium content of 0.23 mg/kg, which is explained by the impact of the forest fire in 2022 (Figure 5). In 2024, the average cadmium content was 0.19 mg/kg (Table 5). Research conducted in the forests of South Baikal and Buryatia also noted an accumulation of cadmium content after a fire [Krasnoschekov, 2011; Sosorova et al., 2013].

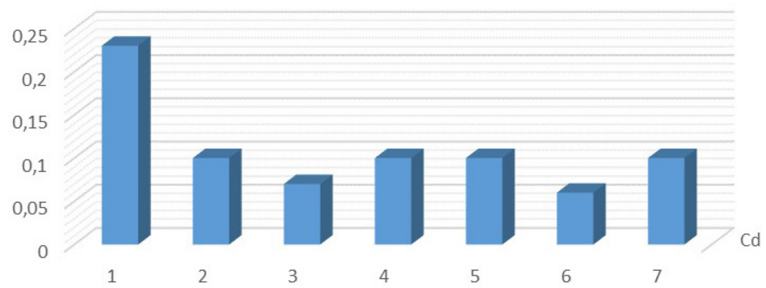

Figure 5. Cadmium content in the soil cover of the Amankaragai forest. On the vertical axis – heavy metal content in mg/kg, on the horizontal axis – key site numbers

Table 5. Variational-statistical indicators of heavy metals in the soils of the Amankaragay forest for 2024, in mg/kg

Parameters	X±Sx	lim	σ	C_V, %
Al	14231.13±564.15	12195.06–16661.43	1489.36	10.47
Cd	0.19±0.83	0.18-0.20	6.2	3.8
Cr	43.08±8.31	18.11–84.46	8.31	47.25
Fe	25280.99±2304.95	13683.08–65486.93	14487.41	45.44
Mn	592.97±57.27	451.1–1077	151.77	25.59
Pb	19.95±1.87	11.17–27.18	4.94	24.78
Va	24.50±1.61	20.73–33.34	3.95	16.11
Zn	48.19±4.02	15.77–70.78	10.66	22.13
Hg	0.0083±0.0013	0.0027–0.0150	0.0032	38.15

Chromium (Cr) is a naturally occurring element present in the earth's crust, with oxidation states (or valence states) ranging from chromium (II) to chromium (VI) [Jacobs and Testa, 2005]. The average chromium content in the soils is 45.87 mg/kg, ranging from 29.3 to 97.2 mg/kg, with an average coefficient of variation of 36.28%. The maximum concentration of total chromium content in the upper soil horizon, 97.2 mg/kg, was found in key area No. 1. The minimum total chromium content, 29.3 mg/kg, is characteristic of key area No. 3, which was not affected by the forest fire.

In 2024, the chromium content ranges from 18.11 to 84.46 mg/kg, with an average content of 43.08 mg/kg. The maximum chromium content of 84.46 mg/kg was found in key area No. 2. The minimum total chromium content of 18.3 mg/kg is characteristic of key area No. 6.

Iron (Fe) is one of the most common elements. Iron occupies the 26th elemental position in the periodic table. Iron is a most crucial element for growth and survival of almost all living organisms. The source of iron in surface water is anthropogenic and is related to mining activities [Valko et al., 2005].

Iron in the soil is primarily present in the form of oxides and hydroxides, found as small particles or bound to the surface of certain minerals. The lower the pH value, the higher the iron content, while in alkaline conditions, its content is minimal. The pH of the studied soils is weakly acidic, with an average content of 6.3.

The average iron content in the soils of the studied area in 2023 was 20,427.86 mg/kg, which is lower than the Clarke value for iron in soils (38.000 mg/kg). Figure 6. The iron content ranged from 10.533 to 39.364 mg/kg, with an average coefficient of variation of 29.90%. The maximum iron concentration of 39.364 mg/kg was found in key plot No. 1.

The average iron content in 2024 was 25,280.99 mg/kg, which is higher compared to 2023. The iron content ranged from 13,683.08 to 65,486.93 mg/kg. Maximum concentrations of iron were found in key plots No. 2 (22,768.62 mg/kg) and No. 7 (65,486.93 mg/kg), both of which were affected by fire. The minimum iron content of 13,683.08 mg/kg was observed in key plot №4, which experienced a fire in 2004.

Manganese (Mn) is a naturally occurring component of the earth's crust. After iron, Mn is the second most abundant metal. Research has shown that the total manganese content in the soils of the humus-accumulative horizon ranges from 465 to 1363 mg/kg, with an average of 750 mg/kg. The maximum manganese concentration of 1363 mg/kg was recorded in key plot No. 7, which does not exceed the maximum permissible concentration (MPC) of 1500 mg/kg in the soil. Figure 5. The minimum manganese concentration of 465 mg/kg was observed in key plot No. 3.

In 2024, the manganese content ranged from 451.1 to 1077 mg/kg, with an average of 592.97 mg/kg. The maximum manganese content of 1077 mg/kg was found in key plot No. 7. The minimum manganese content of 451.1 mg/kg was observed in key plot No. 1.

Lead (Pb) is a naturally occurring bluish-gray metal present in small amounts in the earth's crust. Although lead occurs naturally in the

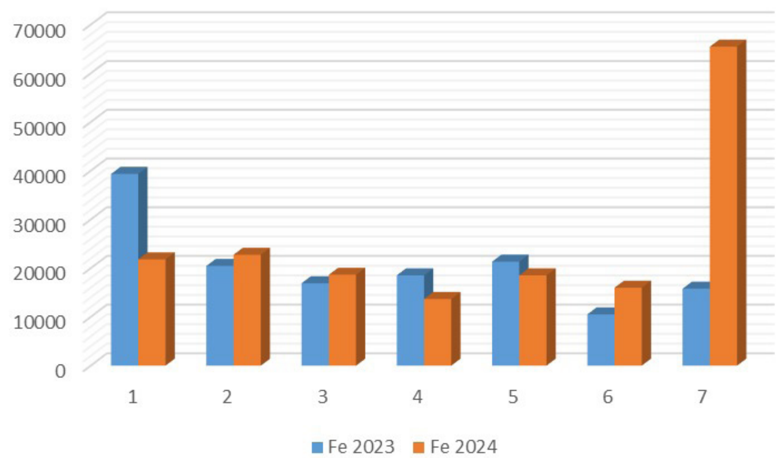

Figure 6. Iron content in the soil cover of the Amankaragai forest in 2023 and 2024. On the vertical axis, the content of heavy metals in mg/kg; on the horizontal axis, the numbers of key plots

environment, anthropogenic activities such as fossil fuels burning, mining, and manufacturing contribute to the release of high concentrations.

The average content of total lead in the soils was 12.04 mg/kg, which is lower than the Clarke value in the Earth's crust (16 mg/kg). The highest concentrations of lead, 20.33 mg/kg, which do not exceed the maximum allowable concentration (MAC) of 32 mg/kg, were found in the upper soil horizon of key plot No. 6. The minimum content was observed in key plot No. 3.

The average lead content in 2024 was 19.95 mg/kg, which exceeds the average content compared to 2023 (Figure 7). Lead content varies from 11.17 to 27.18 mg/kg. The highest concentrations of lead were found in key plot No. 3 (27.18 mg/kg) and No. 1 (22.44 mg/kg), which do not exceed the maximum allowable concentration (MAC) of 32 mg/kg. It should be noted that the key plot with the highest lead content, No. 3 (27.18 mg/kg), is a background plot, not exposed to the forest fire. This suggests that some burned soils actively alter their original geochemical composition, purging themselves of certain elements with carcinogenic properties (e.g., Hg, Pb).

The minimum lead content of 11.17 mg/kg is characteristic of key plot No. 6, which is a background plot, not exposed to fire.

Vanadium (V) is one of the most abundant trace elements in the Earth's crust. In the environment, it occurs in various valence states (−III, −I, 0, +II, +III, +IV, +V), with the most common pentavalent (+V) and tetravalent (+IV) states [Gan et al., 2020].

Vanadium in the humus-accumulative horizon ranges from 42.8 to 154.7 mg/kg, with an average content of 69.58 mg/kg. The maximum vanadium content of 154.7 mg/kg, which exceeds the maximum permissible concentration (MPC) of 150 mg/kg, is typical for key site No. 1. The minimum vanadium concentrations of 42.8 and 49.7 mg/kg are characteristic of key sites No. 6 and No. 3, respectively, which were not affected by the fire.

In 2024, vanadium content ranges from 20.73 to 33.34 mg/kg, with an average content of 24.50 mg/kg. The maximum vanadium content of 33.34 mg/kg was found in key site No. 2. The minimum vanadium content of 20.73 mg/kg is characteristic of key site No. 5.

Zinc (Zn) is one of the most commonly used metals and can enter the environment as a result of numerous industrial processes. An increase in content is observed after forest fires. The average zinc content in 2023 was 55.78 mg/kg, which exceeds the zinc Clarke value of 50 mg/kg, with a range of limits from 18.1 to 102.6 mg/kg. The variation coefficient of 37.65% indicates significant variability in the spatial distribution of zinc. The minimum total zinc content of 18.1 mg/kg is characteristic of key site No. 6, 37.1 mg/kg for key site No. 3, both of which were not affected by the forest fire. The maximum zinc concentrations are typical for key site No. 1 (88.7 mg/kg) and No. 7 (102.6 mg/kg), which corresponds to the MPC of 100 mg/kg (Figure 8).

The average zinc content in 2024 was 48.19 mg/kg, which does not exceed the average content compared to 2023. Zinc content ranges from 15.77 to 70.78 mg/kg. The maximum zinc concentrations were found at key site No. 7 (70.78 mg/kg) and No. 3 (61.45 mg/kg), both of which do not exceed the MPC (100 mg/kg). The minimum zinc content of 15.77 mg/kg is characteristic of key site No. 6, which is a background site not affected by the fire.

Zinc compounds are mobile and biologically available. As they are biophilic, they are released into the atmosphere during combustion due to the burning of plants. The soil environment studied is acidic (pH close to 6), which promotes greater

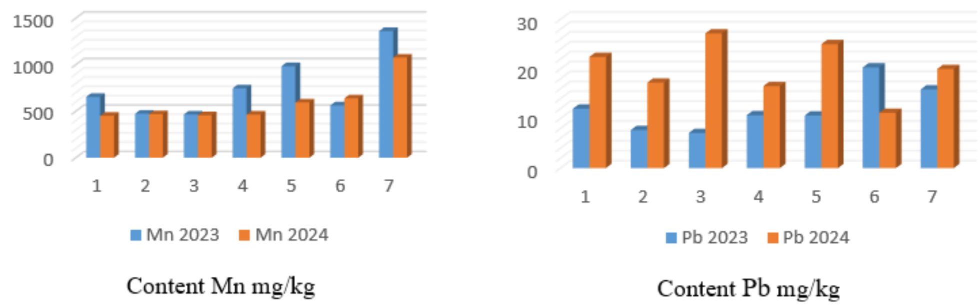

Figure 7. Manganese and lead content in the soil cover of the Amankaragai forest in 2023 and 2024.

Figure 8. Key site No. 7

mobility of zinc. Moreover, atmospheric deposition of Zn exceeds its removal through leaching and biomass formation [Kabata-Pendias, 1989]. Analytical data show that its content at the background site No. 3 (61.45 mg/kg) is higher than at the burned sites No. 1 and No. 2 (49.67 mg/kg and 47.48 mg/kg, respectively) (Figure 9).

Mercury is a heavy metal belonging to the transition element series of the periodic table. It is unique in that it exists or is found in nature in three forms (elemental, inorganic, and organic), with each having its own profile of toxicity [Dopp et al., 2004]. The mercury content in soils depends on the soil type and subtype, as well as their agrophysical and agrochemical characteristics [37]. A review of the literature on mercury contamination of the Earth's surface, soils, and plants, and the transformation of mercury compounds [38, 39], indicates that mercury deposition on land surfaces primarily occurs in its oxidized form (Hg^{2+}). Its transformations are primarily associated with the redox potential of the environment and biological and chemical methylation processes.

The average mercury content in 2023 was 0.0111 mg/kg, which is above the soil Clarke value (0.001 mg/kg). Mercury content fluctuates between 0.0033 and 0.0220 mg/kg. The highest mercury concentration of 0.0220 mg/kg, which does not exceed the MPC (2.1 mg/kg), was found in the upper soil horizon of key site No. 3. The minimum mercury content of 0.003 mg/kg is characteristic of key site No. 1 (Figure 10).

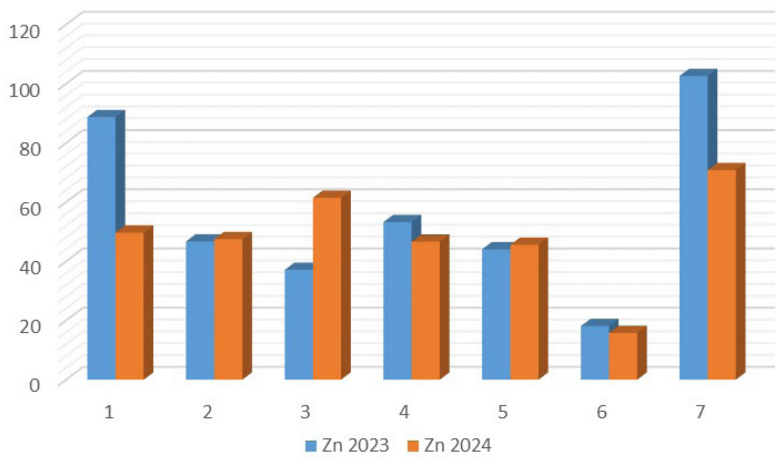

Figure 9. Zinc content in the soil cover of the Amankaragai Forest. The vertical axis represents the content of heavy metals in mg/kg, and the horizontal axis represents the numbers of key sites

The average mercury content in 2024 was 0.0083 mg/kg, which is higher compared to 2023. Mercury content ranges from 0.0027 to 0.0150 mg/kg. The highest mercury concentrations were found at key site No. 4 (0.0150 mg/kg), which is a background site not affected by the forest fire. The minimum mercury content of 0.0027 mg/kg is characteristic of key site No. 6, which is also a background site not affected by the fire. The uneven distribution of mercury allows for the conclusion that burned soils alter their original geochemical composition, gradually clearing out mercury.

We surveyed 7 key sites, among which the most affected by the forest fire are key sites No. 5 and No. 7. A comparative analysis of control (background) sites and key sites affected by the forest fire showed that, for all heavy metals except manganese and mercury, the content was higher at the sites where the fire occurred. Table 6. Analysis The conducted studies on the exceeding of permissible concentrations of heavy metals are important, as excessive concentrations of heavy metals in soils can have a negative toxic impact on the natural regeneration of pine.

Thus, we have identified elevated concentrations of the following elements: aluminum, with the maximum concentration in the upper soil horizon of 78.938 mg/kg found at key site No. 1, which is 11 times higher than the aluminum Clarke value for soils of the Earth according to A.P. Vinogradov; the maximum concentrations of iron, 39.364 mg/kg, were found at key site No. 1, which exceeds the Clarke value for iron in soils (38.000 mg/kg); the maximum vanadium content of 154.7 mg/kg, which exceeds the maximum permissible concentration (MPC) of 150 mg/kg, is characteristic of key site No. 1; and the maximum zinc concentrations were found at key site No. 7, 102.6 mg/kg, which corresponds to the MPC of 100 mg/kg.

Table 6. Average content of heavy metals in control (background) sites and sites affected by fire

Parameters	Control (background)	After the fire
Al	13843.44	14618.82
Cd	0.17	0.19
Cr	29.46	56.69
Fe	16118.17	32153.10
Mn	647.85	519.8
Pb	18.3	21.18
Va	21.81	27.19
Zn	41.28	53.38
Hg	0.0096	0.0070

The analysis of soil contamination in the Amankaragai Forest with heavy metals shows that concentrations toxic to plants have not been detected. The analysis of soil contamination at key sites affected by the forest fire indicates that the concentrations of vanadium and zinc are within the permissible limits (MPC). The concentrations of all other heavy metals do not exceed the MPC, suggesting that heavy metals at sites affected by the forest fire do not have a toxic impact on the natural regeneration of pine. The study of post-fire changes in heavy metals in the soil cover

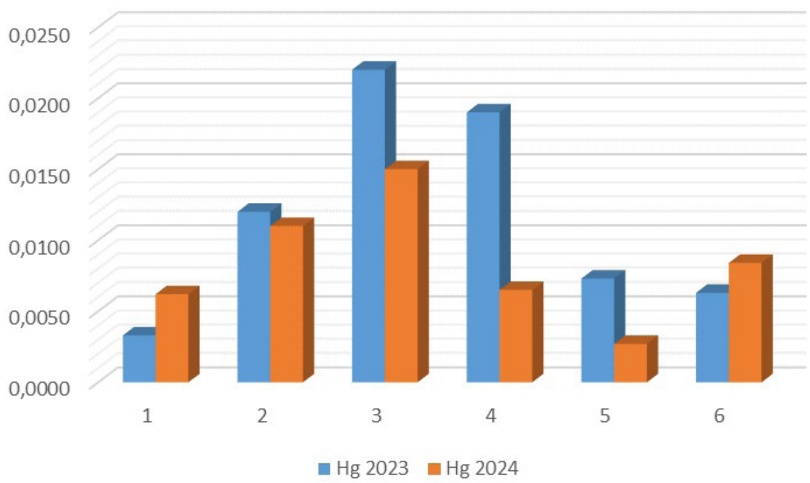

Figure 10. Mercury content in the soil cover of the Amankaragai Forest in 2023 and 2024. The vertical axis represents the content of heavy metals in mg/kg, and the horizontal axis represents the numbers of key sites

contributes to understanding the pathways for the restoration of the pine forest.

Factors hindering the natural regeneration of pine forests include deep burning of the forest litter and soil cover, mechanical damage to pine seedlings caused by equipment used for clearing burned areas, and the fungus *Rhizina undulata* (Fr.), which infects the roots of conifer trees. After the 2022 fire, a large number of fruiting bodies of the root pathogen *Rhizina undulata* appeared in the forest.

During our field studies, we observed uneven natural regeneration of Scots pine after the fire. Seedling emergence is primarily associated with moist lowlands and loosened soil areas. The main factor contributing to the natural restoration of burned forests is abundant precipitation in both spring and autumn. The process of natural recovery after the fire is uneven. The prolonged drought in 2022, which contributed to the rapid spread of the fire, also hindered natural regeneration in the forest in recent years. The summer of 2023 was also dry, with only prolonged rains at the end of the summer helping the emergence of Scots pine seedlings. The seeds that did not germinate in the spring began to sprout en masse in the autumn, primarily in low-lying areas where moisture is retained longer. Additionally, during the field survey of the burned areas, spring germination was observed in areas where winter logging had taken place, with skidding of fallen trees damaging the topsoil and facilitating seed placement in favorable, relatively prepared soils for germination. For the pine forests in this region, precipitation and soil moisture content play a key role.

The increasing frequency of forest fires in Kazakhstan has significant implications for land-use planning and wildfire management policy. These implications extend across ecological, social, and economic domains, requiring a comprehensive and forward-thinking approach to reduce risks and enhance resilience.

Further research on forest fires, their impacts, and mitigation strategies tailored to Kazakhstan's ecosystems and climate is essential. Utilizing historical wildfire data for modeling future risks and informing land-use planning is crucial. Understanding the consequences of forest fires is vital for protecting ecosystems, livelihoods, and economic stability.

The conducted analysis highlighted the importance of assessing the content of heavy metals in the soil to understand the successful regeneration of Scots pine during restoration efforts following a fire. Moreover, these results provide insights into ecosystem restoration strategies based on soil conditions after forest fires. Further research, including the physical, chemical properties, and the content of mobile forms of heavy metals, is crucial for developing a comprehensive understanding of the impact of high-intensity forest fires on soil properties and ecosystem dynamics. This expanded knowledge base will be vital for guiding effective management and conservation methods in fire-affected forest landscapes.

CONCLUSIONS

Based on the obtained results, the following conclusions were presented:

1. The studied soils are characterized by an acidic reaction and low humus content.
2. In 2023, based on the average concentrations of heavy metals (mg/kg) in the soils of the Amankaragai Forest, they are ranked in the following descending order: Al (27837) > Fe (20427.86) > Mg (4287.29) > Na (3293.14) > Mn (750) > V (69.58) > Zn (55.78) > Cr (45.87) > Pb (12.04) > Cd (0.11) > Hg (0.0111).
3. Elevated concentrations of aluminum (78938 mg/kg), cadmium (0.23 mg/kg), chromium (97.2 mg/kg), iron (39364 mg/kg), vanadium (154.7 mg/kg), and zinc (88.7 mg/kg) were found in the upper soil horizon of key site No. 1.
4. The observed heterogeneity in the content of heavy metals in the soil cover of key sites in the Amankaragai Forest is due to the influence of forest fires.
5. The analysis of heavy metal contamination in the soils of the Amankaragai Forest shows that toxic concentrations for plants have not been detected. The analysis of soil contamination at key sites affected by the forest fire shows that the concentrations of vanadium and zinc are within the permissible limits (MPC). The concentrations of all other heavy metals do not exceed the MPC.
6. As a result of high-temperature effects, there is active migration of heavy metals. The data obtained indicate the need for further research on the mobile forms of heavy metals during the post-fire development of soils, as well as the transformation of heavy metal compounds and their role in the further development of soils.

Acknowledgements

This study was undertaken as part of grant funding for scientists awarded for scientific and (or) scientific and technical projects from 2023 to 2025 by the Ministry of Science and Higher Education of the Republic of Kazakhstan (IRN No. AP19678305).

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