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STUDIES OF THE INITIAL STAGES OF PYROGENIC SUCCESSIONS AND SOIL CHARACTERISTICS IN ISLAND PINE FORESTS OF NORTHERN KAZAKHSTAN

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ABSTRACT

This study assessed early post-fire vegetation succession and soil quality in the Amankaragai pine forest of Northern Kazakhstan after severe fires in September 2022. Field studies were conducted in 2023–2024 on control, burned, and cleared-burned plots using geobotanical descriptions, species activity assessment, soil morphological analysis, agrochemical testing, toxicological analysis, and radionuclide measurements. Vegetation recovery followed the pattern of secondary pyrophytic succession, with strong regeneration of fire-surviving pyrophytes and rapid spread of long-rhizomatous grasses, especially *Calamagrostis epigeios*. Cleared burned areas showed increased meadow-steppe and weed species, which may hinder natural pine regeneration. Burned soils lost much of the A0 and A1 horizons, but heavy metals, potentially toxic elements, and gamma-radionuclide activity remained within permissible limits. The results provide useful baseline data for monitoring and restoring fire-affected island pine forests.

Keywords: Kazakhstan, Amankaragai pine forest, Fires, Pyrogenic succession, Species activity, Pyrophyte.

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1. INTRODUCTION

The conservation and sustainable use of biological diversity is one of the key environmental challenges of the modern world. Biodiversity creates the conditions necessary for the biosphere to function and thus serves as a life-supporting basis for humans and the economy. Healthy biodiversity also ensures the environment's capacity to resist negative environmental impacts from human economic activity. At present, high rates of biodiversity loss persist worldwide, which is a significant barrier to sustainable development (Beishov et al., 2019, 2021; Bugubaeva et al., 2023b; Makenova et al., 2023; Simanchuk & Sultangazina, 2023, 2024; Sultangazina et al., 2024).

Forest fires have long functioned as a fundamental disturbance shaping the structure, composition and carbon balance of the world's forest biomes, and they continue to do so under contemporary climate change (Brown & Davis, 1973; Cwynar, 1978; Furyaev & Kireev, 1979; Sannikov, 1983; Senande-Rivera et al., 2022). Over the past two decades, satellite-based inventories indicate a roughly 40% global increase in the spatial extent of forest fires and an approximately two-fold increase in the intensity of extreme fires, with these changes being predominantly concentrated in extratropical and high-latitude ecosystems (Kelley et al., 2025). During the March 2023 – February 2024 fire season alone, 3.9 million km² burned globally, releasing approximately 2.4 Pg C, which is about 16% above the preceding multi-year average, driven largely by record emissions (>9× the historical mean) in Canadian boreal forests and by extreme events in the western Amazon, Greece, Chile and Hawai'i (Jones et al., 2024). Analyses of burned area across 1900–2015 confirm that, while global trends in mean fire frequency have been statistically weak, increases in burned area of ≥50% have been documented in several extratropical forest ecoregions, including the Pacific United States and high-latitude forests, in parallel with a pervasive rise in fire-favourable weather (Jones et al., 2022, 2024). Fire size, in turn, has been shown to amplify post-fire land-surface warming, establishing a positive feedback between climate change and fire-driven terrestrial warming (Zhao et al., 2024). Boreal and temperate forests are particularly exposed to this feedback because their carbon stocks are large and their post-fire recovery is comparatively slow (Eckdahl et al., 2024; Jones et al., 2024; Kelley et al., 2025).

Within this global picture, contemporary wildfire ecology has reframed post-fire dynamics around three

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interlinked concepts: pyrogenic succession, post-fire soil recovery, and pyrodiversity-driven biodiversity restoration. Pyrogenic succession is now understood not as a deterministic return to pre-fire composition but as a joint outcome of fire severity, fire history, drought, residual biotic legacies and the species pool of adjacent unburned stands (Clements, 1916, 1928; Dawe et al., 2022; Day et al., 2023). In dry boreal forests of northwestern North America, trajectories of tree regeneration, understory cover and species diversity continued to change for at least five years after an unusually severe 2014 fire season, with substantial species turnover in every stand type and only partial convergence in species evenness (Dawe et al., 2022). In jack-pine-dominated chronosequences, soil bacteria returned to a shared core community (~95–97% of sequences) by crown closure, whereas fungi (64–77% shared) and arthropods (68–69% shared) supported stage-specific communities at each successional age, implying that all successional stages are required to maintain the full suite of soil biodiversity (Porter et al., 2023). In Western Alpine Scots pine stands, elevation, aspect and distance from seed sources jointly determined short-term post-fire recovery, leading to the conclusion that ecosystem-specific, site-precise restoration strategies outperform uniform active interventions (Mantero et al., 2024).

Post-fire soil recovery has likewise been shown to depend strongly on burn severity and on the parent substrate. Surface and crown fires of medium intensity commonly form a new pyrogenic horizon that differs from its natural analogues in pH (often shifted toward neutral), in humus and nitrogen reserves and in the distribution of ash elements; in pine forests on sandy substrates, the concentration of heavy metals in surface horizons may increase several-fold through combustion of litter and subsequent vertical migration, representing a long-term ecological hazard (Buts et al., 2022, 2023; Maksimova & Abakumov, 2023; Nureev, 2025). Conversely, 30-year afforestation trials using *Pinus sylvestris*, *Larix decidua*, *Betula pendula* and *Quercus robur* on post-fire sandy substrates demonstrate that active reforestation can re-establish near-natural soil-forming processes, producing Podzols with humus horizons comparable in thickness to those of primary-successional post-mining sites (Józefowska et al., 2023). Recent work on post-fire biodiversity now centres on the pyrodiversity hypothesis – the idea that spatial and temporal heterogeneity of fire regimes underpins biodiversity – and on the need to align restoration frameworks with the specific pyrogenic context of each biome (Kelly et al., 2023). Globally, integrated frameworks for post-fire forest restoration now propose six to seven criteria with ~30 indicators, integrating environmental, economic, social, cultural and infrastructural objectives, and stress that excluding post-fire logging and supporting ecosystem-appropriate regeneration are often the single most decisive interventions (Alayan et al., 2022; Lindenmayer et al., 2022; Souza-Alonso et al., 2022).

Within Central Asia, these global and regional processes are particularly relevant to the relict island pine (*Pinus sylvestris* L.) forests of the Turgai depression in Northern Kazakhstan – the Amankaragai, Borovskoy, Arakaragai and Kazanbasy massifs – which grow on ancient eolian sands within a sharply continental, semi-arid climate at the southern margin of the species' range (Pugachev, 1994). Radiocarbon evidence places their origin in the mid-Holocene (approximately 6.000–4.500 years ago), and their flora is exceptionally rich (426 species in 238 genera across 68 families), with a large relict component not represented in the surrounding dry steppe (Pugachev, 1994; Kremenetski et al., 1997). These island pine forests develop under sharply continental and semi-arid climatic conditions with an average annual precipitation of approximately 310 mm, where water availability constitutes an important limiting factor for forest regeneration (Reference and Information Portal "Weather and Climate, 2022). In addition to climatic constraints, long-term agricultural development, intensive logging and repeated wildfires have substantially altered the hydrological regime and biodiversity of these forests (Ministry of Environment and Water Resources of the Republic of Kazakhstan, 2014). Because total forest cover in Kazakhstan is only 4.7% and protective forests account for 96% of the national forest fund, with 86% of the country's biological diversity concentrated in these landscapes, any disturbance to coniferous stands, which together occupy roughly 9.5% of the forest fund, has disproportionately large ecological consequences (United Nations Development Programme, 2018; Danchenko & Kabanova, 2020). The September 2022 fires alone affected 33824.3 ha of forest-covered land and 42,927.8 ha of non-forest land in Kostanay Region, following 5183.7 ha of forest-land burned in 2021 (Ministry of Ecology, Geology and Natural Resources of the Republic of Kazakhstan, 2021; Ministry of Ecology and Natural Resources of the Republic of Kazakhstan, 2023). During 2022–2025, comprehensive ecological monitoring of the burned Amankaragai pine forest involved assessments of vegetation recovery, soil properties and remote-sensing observations, providing the basis for the present integrated field investigation (Nugmanov et al., 2022; Bugubaeva et al., 2023a, 2023b; Simanchuk & Sultangazina, 2024; Sultangazina et al., 2024; Zarubin et al., 2025). Recent Kazakhstan-focused studies have begun to quantify post-fire heavy-metal redistribution, post-fire vegetation regeneration via remote-sensing indices and the wider consequences of fire for biodiversity, air quality and the hydrological regime of sandy massifs (Atantayeva et al., 2024; Zhanbossinova et al., 2024; Lyavdanskaya et al., 2025; Ozgeldinova et al., 2025; Zhanguzhina et al., 2025). Nevertheless, three explicitly identified research gaps remain.

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First, although the global literature on pyrogenic succession has expanded rapidly, there are still very few studies that quantify the very early (1–2 year) post-fire stages in *island* pine forests growing on eolian sands in a dry-steppe climate, where pyrophyte survival, root-rhizome resprouting, and the encroachment of meadow-steppe species interact in a particularly distinctive way (Vlasenko & Rybashlykova, 2024; Lyavdanskaya et al., 2025; Skrobala et al., 2025; Khapugin & Ruchin, 2025). Second, although post-fire soil chemistry in pine forests has been widely investigated elsewhere (Buts et al., 2022, 2023; Nureev, 2025), integrated assessments combining soil morphological change, mobile and total element forms, agrochemical indicators and gamma-radionuclide activity in island pine soils remain absent. Third, while restoration frameworks tailored to boreal, Mediterranean and temperate forests are now available (Alayan et al., 2022; Souza-Alonso et al., 2022; Lindenmayer et al., 2022; Mantero et al., 2023), no such framework has been calibrated for the arid-steppe island pine forests of Northern Kazakhstan, where water-limited conditions, sandy substrates, and extreme summer temperatures impose constraints on natural regeneration that have no direct analogue in temperate Europe (Atantayeva et al., 2024; Lyavdanskaya et al., 2025).

The present study was designed to address these knowledge gaps through an integrated ecological and soil-based assessment. Unlike previous investigations conducted in Kazakhstan, which have primarily focused on remote sensing of post-fire regeneration (Zhanguzhina et al., 2025), heavy-metal contamination (Ozgeldinova et al., 2025), or the broader conservation status of pine forests (Atantayeva et al., 2024; Zhanbossinova et al., 2024) and international studies that have largely examined boreal or Mediterranean pine forest ecosystems (Dawe et al., 2022; Day et al., 2023; Mantero et al., 2024; Buts et al., 2023; Nureev, 2025), this study provides the first comprehensive field-based evaluation of post-fire ecological recovery in the Amankaragai island pine forest. Specifically, it (i) quantifies species activity during the early stages of pyrogenic succession using paired burned and unburned (control) plots, (ii) compares post-fire vegetation dynamics under burned-only and cleared-and-logged management regimes, (iii) characterizes the morphological properties of the upper soil horizons, (iv) determines both mobile and total concentrations of potentially toxic elements together with major rock-forming oxides, and (v) evaluates gamma-radionuclide activity in forest soils. By integrating vegetation and soil quality indicators within a unified comparative framework and employing replicated sampling across the Kalininskoye and Novonezhinskoye forest districts of the Semiozernoye Forestry Institution, this study establishes the first quantitative multi-indicator baseline for assessing post-fire ecosystem recovery and evaluating the effectiveness of future restoration strategies in the Amankaragai pine forest.

The aim of the present study was to investigate post-fire changes in vegetation succession and plant community development following the September 2022 combined fire in the Amankaragai island pine forest and to evaluate the physical, chemical, and radiological characteristics of soils in both burned and unburned (control) sites. We hypothesized that the September 2022 combined fire significantly modified early vegetation succession and upper soil-horizon properties in the Amankaragai island pine forest by promoting the establishment and expansion of pyrophytic and meadow-steppe species, increasing the synanthropization of herbaceous vegetation, and reducing the natural regeneration potential of *Pinus sylvestris*, while maintaining concentrations of potentially toxic elements and gamma-radionuclide activity within internationally accepted permissible limits.

To test this hypothesis, the study pursued the following objectives:

1. To quantify species activity during the initial stages of pyrogenic succession in the Amankaragai island pine forest, Auliekol District, Kostanay Region, Kazakhstan.
2. To evaluate the survival, abundance, and ecological activity of pyrophytic species following the September 2022 fire.
3. To investigate the development and succession of meadow-steppe plant communities in post-fire habitats.
4. To characterize the floristic composition and community structure of unburned (control) forest stands.
5. To assess the morphological characteristics of the upper soil horizons across unburned, burned, and post-fire managed forest sites.
6. To determine the agrochemical properties of soils together with the mobile and total concentrations of major and potentially toxic elements in the investigated forest plots.
7. To evaluate gamma-radionuclide activity in soil samples as an indicator of post-fire radiological conditions.

2. MATERIALS AND METHODS

2.1. Objects of Research

The study was conducted in the Amankaragai pine forest, located in Auliekol District, Kostanay Region, northern Kazakhstan (Fig. 1). The Amankaragai forest is one of the relict island Scots pine (Pinus sylvestris L.) forests of the Turgai Depression and occurs within a sharply continental, semi-arid dry-steppe zone. The study area is situated approximately between 52.409° and 52.506° N latitude and 64.069° and 64.209° E longitude.

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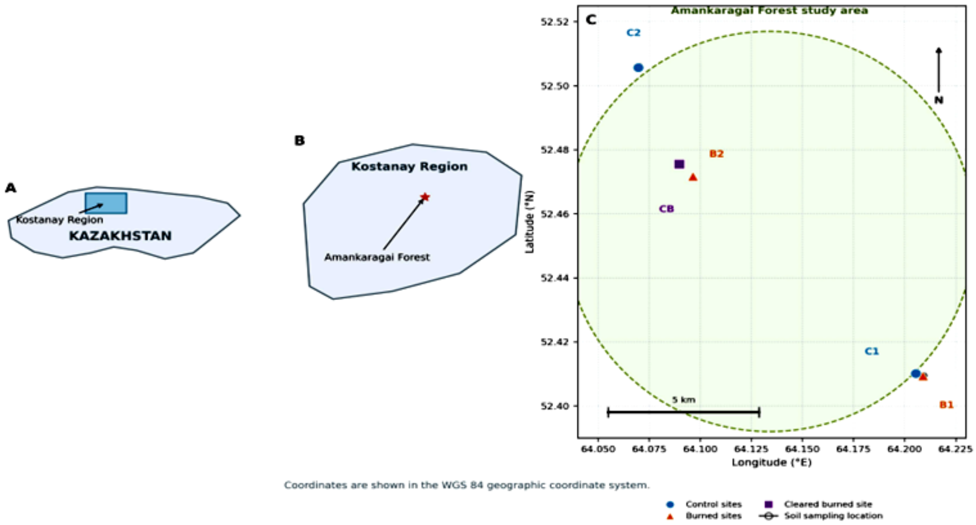

Fig. 1: Geographic location of the Amankaragai pine forest and study sites in northern Kazakhstan. A, location of Kostanay Region within Kazakhstan; B, location of the Amankaragai forest within Kostanay Region; C, principal vegetation-monitoring sites and soil-sampling locations. Coordinates are shown in the WGS 84 geographic coordinate system.

Field investigations were conducted within the Kalininskoye and Novonezhinskoye forest districts of the Semiozernoye Forestry Institution. Five principal vegetation-monitoring sites were included: two unburned control sites, two burned sites where the fire-damaged tree stands remained in place, and one cleared burned site from which the burned trees had been removed in spring 2023. The locations and coordinates of the principal monitoring sites were as follows:

- Control-1: 52.410100° N, 64.205383° E;
- Burned Area-1: 52.409356° N, 64.208874° E;
- Control-2: 52.505632° N, 64.069678° E;
- Burned Area-2: 52.471740° N, 64.096280° E;
- Cleared Burned Area: 52.475540° N, 64.089670° E.

Soil sampling was performed at nine georeferenced locations within the same study area, comprising three locations in Novonezhinskoye Forestry and six locations in Kalininskoye Forestry. Four horizon-specific samples were obtained from each location, resulting in 36 soil samples. The complete coordinates of the soil-sampling locations and the corresponding genetic horizons are presented in Appendix 1.

According to Makhanova et al. (2022), the total forest-covered area of the Amankaragai forest was 33,370.5 ha, including 13,235.55 ha of sparse forest and 20134.95 ha of dense forest. Over a 28-year period, the forest-covered area decreased by 5506.5 ha, and more than 11210 ha were affected by logging and fires between 1993 and 2023. Despite substantial anthropogenic disturbance, the forest ecosystem has been characterized as a relatively stable geosystem with a capacity for recovery. According to N. Makhanova et al. (2022), the total forest-covered area was 33370.5 ha, including 13235.55 ha of sparse forest and 20134.95 ha of dense forest. Over 28 years, the forest-covered area decreased by 5506.5 ha. From 1993 to 2023, more than 11210 ha were affected by logging and burned areas. Despite significant anthropogenic disturbances, the authors concluded that the forest ecosystems of the Amankaragai pine forest constitute a stable geosystem and are capable of recovery.

The study was conducted using a comparative field-monitoring design in the Amankaragai pine forest during the 2023 and 2024 growing seasons, corresponding to the first and second years following the September 2022 wildfire. Five permanent monitoring plots representing the principal post-fire ecosystem conditions were established within the Kalininskoye and Novonezhinskoye forest districts of the Semiozernoye Forestry Institution. These included two unburned control plots (Control-1 and Control-2), two burned forest plots with standing dead trees (Burned Area-1 and Burned Area-2) and one burned plot that had undergone salvage logging and removal of burned timber (Cleared Burned Area).

For each monitoring plot, ten independent geobotanical relevés were completed using standard geobotanical methods. Forest vegetation was surveyed on 625 m² plots, whereas herbaceous vegetation was assessed on 100 m² plots. Soil sampling was conducted at the same monitoring sites to enable direct comparison between vegetation

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recovery and soil characteristics. Samples were collected from the major genetic soil horizons for morphological, agrochemical, toxicological, and radionuclide analyses. Monitoring plots were selected purposively to represent the major post-fire management and disturbance conditions within the study area; therefore, random allocation of sampling sites was not applied (Fig. 2).

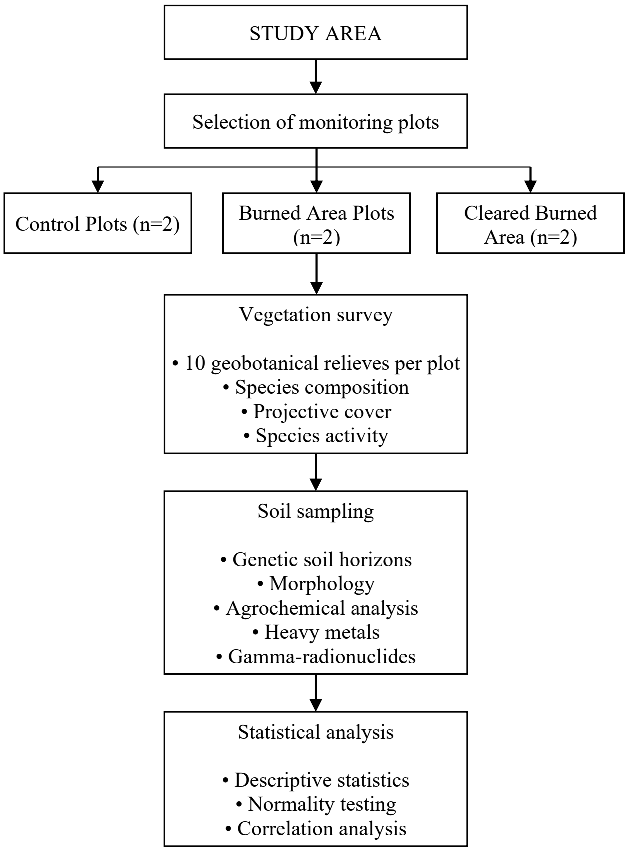

Fig. 2: Experimental design and sampling workflow of the study.

2.2. Methods for Assessing Pyrogenic Successions. Floristic Analysis

The vegetation cover of the pine forests of the Turgai depression, including the Amankaragai pine forest, has been studied in considerable detail by Pugachev (1994), who emphasized the floristic similarity of the island pine forests and their high floristic richness: 426 species and 238 genera from 68 families, with a large number of species belonging to the relict complex. To study the nature of natural overgrowth in the burned areas of the Amankaragai pine forest, monitoring plots were established within the territory of the Semiozernoye Forestry Institution (Fig. 1).

The following sites within the Kalininskoye and Novonezhinskoye forest districts were selected as monitoring plots:

1. An area unaffected by fire (controls 1 and 2);
2. An area affected by fire with the burned tree stand remaining in place (burned areas 1 and 2);
3. An area where the forest was cut down and removed in spring 2023 (cleared burned area).

The initial stages of pyrogenic successions were studied in 2023–2024. Geobotanical descriptions were carried out according to standard methods (Lavrenko, 1938; Korchagin, 1964). In forested areas, the description plot area was 625 m². In plots with herbaceous cover, the sample plot area was 100 m². For each variant, 10 standard geobotanical descriptions were performed, and the number of species, occurrence (%), and partial projective cover (%) were determined. In total, 80 geobotanical descriptions were completed.

Projective cover was assessed using the combined J. Braun-Blanquet scale (Braun-Blanquet 1964): + (0.5%); 1 – 1–4%; 2 – 5–9%; 3 – 10–24%; 4 – 25–49%; 5 – 50–74%; 6 – 75–100%.

Constancy classes (CC) in the tables are given in Roman numerals according to a five-point scale: I – the species is present in less than 20% of descriptions; II – 21–40%; III – 41–60%; IV – 61–80%; V – in more than 80% of descriptions (Kazanskaya et al., 1977). For the overall assessment of the coenotic position of a species, a complex indicator of species activity is used. This indicator reflects the degree of ecological success of a species within a given territory and represents one expression of the "weight of the species" in the given flora (Savinov & Nikitin, 2017; Kuprijanov et al., 2018).

Species activity was calculated in the IBIS system (Zverev 2007) using formula (1):

$$Act = \sqrt{\frac{C \times 100\%}{N} \times \frac{\sum_{i=1}^{N} A_i}{N}} = 10 \times \frac{\sqrt{C \times A_{\Sigma}}}{N}\% \quad (1)$$

Where Act is the calculated activity of the taxon for the monitoring area, expressed as a percentage (0–100%);
N is the number of sample plots;
C is the constancy of the taxon, that is, the absolute number of sample plots where the taxon was recorded;
A_i is the projective cover of the taxon in the i-th sample plot;
A_{Σ} is the sum of the projective covers of the taxon across all sample plots.
The synanthropization coefficient was calculated using the formula proposed by Prokopyev et al., (2007).

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$$K_s = \sum_{i=1}^{N_a} a_i \times 100 \div (\sum_{i=1}^{N_a} a_i + \sum_{i=1}^{N_b} b_i) \quad (2)$$

Where
K_s is the synanthropization coefficient;
a_i is the occurrence of synanthropic species;
N_a is the number of synanthropic species;
b_i is the occurrence of hemerophobic species;
N_b is the number of hemerophobic species.

Under anthropogenic and technogenic loads, herbaceous vegetation responds first. Based on characteristic features, six stages of digression of herbaceous vegetation are distinguished (Valendik, 1996). In determining these stages, the share of the trampled area and several characteristics of the vegetation cover and litter were taken into account. The first stage is characterized by undisturbed litter and a complete set of herbaceous species typical of the given forest type, with numerous individuals of different age groups. The degree of disturbance of the grass stand is 0.7–0.8%; plant communities are complete and show no signs of digression.

At the second stage, paths occupy less than 5% of the area. Litter trampling begins, and edge species start to penetrate under the forest canopy. The degree of disturbance of the grass stand is 1.0–5.0%; plant communities are incomplete but show no signs of digression. At the third stage of digression, the transformed surface occupies 10–15% of the area. The thickness of the litter decreases, illumination increases, the upper forest canopy, young growth and undergrowth become sparse, and meadow and weed species begin to invade. Seedlings of coenosis-forming tree species are almost absent. The degree of disturbance of the grass stand is 5.0–10.0%; plant communities show the first signs of digression.

At the fourth stage, the path network occupies 15–20% of the area. A specific structure is formed, consisting of alternating patches of young growth and undergrowth separated by glades and paths. In glades, the litter is destroyed, meadow grasses expand, and the soil becomes turfed. Young growth remains only under the protection of clumps, and its vitality is very low. The degree of disturbance of the grass stand is 10.0–15.0%; plant communities show significant litter disturbance. At the fifth stage of digression, paths occupy more than 60.0% of the territory. Only patches of vegetation, fragments of weeds, and annual plants remain. Young growth is almost completely absent. Illumination is sharply increased. All remaining trees are diseased or mechanically damaged, and in most trees, the roots protrude above the soil surface. The degree of disturbance of the grass stand is 15.0–20.0%; soil turfing occurs with alternating clumps. At the sixth stage of digression, a significant part of the area is devoid of vegetation, and only patches of weeds and annual plants remain. The degree of disturbance of the grass stand is 60.0–100.0%.

2.3. Studies of Soil Quality Indicators

The assessment of soil morphological features was carried out in accordance with scientific recommendations. The features of soil layers in various control plots were taken into account, including forest areas unaffected by fire, burned forest areas, and other plots (Durasov, 1958, 1959; Malanyin & Smetana, 1989; Baisholanov, 2017).

Soil samples were collected from the studied plots with consideration of soil layer or horizon depth and with recording of geographic coordinates (Appendix 1). Soil sampling for studies of agrochemical and toxicological indicators was carried out in accordance with the regulatory requirements of the Republic of Kazakhstan and scientific recommendations, including regulatory rules for establishing water protection zones and belts, rules for conducting agrochemical soil surveys in the Republic of Kazakhstan, and methodological guidelines for conducting comprehensive agrochemical surveys of agricultural soils (International Organization for Standardization, 2017; Ministry of Agriculture and Food of the Russian Federation, 1994; Ministry of Agriculture of the Republic of Kazakhstan, 2015; State Committee of the USSR for Standards, 1989).

One composite sample was collected from each elementary plot. Point samples taken from the depth of the arable layer, from 0 to 30 cm, were collected with consideration of the presence of the humus horizon. A specific procedure was used to form a single sample mass from 20–25 point samples, with the total weight of the sample mass being at least 1.5 kg. During the work, a composite soil sample was collected from each plot subject to analysis. To create a composite sample, at least 25 individual point samples were used, with a total mass of no less than 2 kg. After delivery to the laboratory, the samples were dried and stored in a designated room. Each sample was assigned an identification code. It should be noted that the soil sampling points practically corresponded to the locations where the floristic analysis was carried out. The coordinates of the soil sampling points are given in Appendix 1.

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Laboratory analyses of soil quality and toxicological properties were conducted in accordance with internationally recognized national standards and regulatory guidelines for soil sampling, preparation, and analytical procedures (Committee for Standardization and Metrology of the USSR, 1991a, 1991b; Committee for Technical Regulation and Metrology of the Ministry of Investment and Development of the Republic of Kazakhstan, 2015; Committee for Technical Regulation and Metrology of the Ministry of Trade and Integration of the Republic of Kazakhstan, 2013; Federal Agency for Technical Regulation and Metrology, 2016a, 2016b, 2021; State Committee of the USSR for Standards, 1985a, 1985b, 1985c, 1985d, 1985e, 1986). Prior to analysis, all soil and ground samples were oven-dried at 110–120°C and gently crushed to disaggregate soil aggregates. The dried samples were subsequently homogenized by grinding with an SBM 200 Siebtechnik disc mill (Siebtechnik GmbH, Germany) to obtain a particle size of ≤2–3 mm. The homogenized samples were then processed for physicochemical, elemental, and radiological analyses.

The pH of the soil environment was assessed by extracting water-soluble salts from the soil with distilled water at a soil-to-water ratio of 1:5 and determining the specific electrical conductivity of the aqueous extract using a pH meter according to GOST 26423-85. Organic matter, or humus, in the soil was determined by photometric and gravimetric methods according to GOST 26213-91. These methods are based on the oxidation of organic matter with a potassium dichromate solution in sulfuric acid and the subsequent determination of trivalent chromium equivalent to the organic matter content. Nitrate content was determined according to GOST 26951-86. Mobile phosphorus and potassium compounds were determined according to GOST 26205-91. The method is based on the extraction of these compounds from soil using an ammonium carbonate solution, followed by the determination of phosphorus as a blue phosphomolybdenum complex on a spectrophotometer and potassium on a flame photometer. A UV-1900i Shimadzu double-beam spectrophotometer manufactured in Japan was used.

Mobile sulfur, including the total content of sulfates and hydrosulfates, was determined according to GOST 26490-85. The method consists of extracting and precipitating mobile sulfur from the soil in the form of sulfates using barium chloride, followed by turbidimetric determination. The content of chloride anions was assessed by titrating chloride ions in an aqueous suspension with a silver nitrate solution according to GOST 26425-85. The content of carbonate and bicarbonate ions was determined by titrating an aqueous extract containing carbonate and bicarbonate ions with sulfuric acid according to GOST 26424-85. Mobile calcium content was determined according to GOST 26487-85. Most indicators of mobile forms of metals were determined using atomic absorption control methods and appropriate sample preparation. Depending on the method used to extract elements from the sample, the analysis results are expressed either as the total content of the corresponding element, the content of acid-soluble forms, or the content of mobile forms.

When assessing the content of heavy metals in total and mobile forms, the recommendations of the national standard ST RK 2.377-2015 were applied. This standard is intended for measuring the mass fraction of vanadium, cadmium, cobalt, manganese, copper, arsenic, nickel, mercury, lead, chromium, and zinc in soil and ground samples using atomic absorption spectroscopy. The main sample preparation procedure consisted of drying and crushing the soil samples, followed by treatment with an ammonium acetate buffer solution. This solution is required for extracting mobile forms of metals and subsequently stabilizing metals in the solution. It should be noted that the optimal method for stabilizing mobile forms of metals in extracts of aqueous soil solutions is the use of an ammonium acetate buffer solution with pH = 4.8. This buffer is recommended for extraction by a number of regulatory documents.

A ContrAA® 800 G high-resolution atomic absorption spectrometer with a continuous spectrum source and electrothermal atomization, manufactured in Germany by Analytik Jena, was used as the main atomic absorption spectroanalyzer. The analyzer makes it possible to determine the content of all major metals in aqueous solutions, including zinc, copper, chromium, nickel, cobalt, potassium, manganese, iron, lead, and cadmium. Where necessary, alternative methods for controlling indicator content were also used, taking into account the accuracy of the methods. For rapid and accurate assessment of the chemical content of total and major rock-forming forms of elements in soil and ground samples, an energy-dispersive X-ray fluorescence spectral analysis method was used in accordance with GOST 33850-2016 "Soils. Determination of chemical composition by X-ray fluorescence spectrometry" and ST RK 2.273-2013 "X-ray spectral measurement procedures. General requirements" (Makhanova et al., 2022; Zarubin et al., 2025). The method provides high analytical efficiency and determination accuracy corresponding to regulatory requirements. The quality and accuracy of the chemical indicator measurements complied with metrological requirements.

Sample preparation for X-ray fluorescence spectral analysis included drying the samples to a dry state at 105–110°C, grinding the samples to a grain size of no more than 2 mm using an SBM 200 Siebtechnik disc mill manufactured in Germany, pulverizing the ground samples into powder with a grain size within 0.05–0.063 mm using a PARATUS mill M102 vibratory grinding mill manufactured in Russia, and placing the powder into special

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cuvettes designed for X-ray fluorescence analysis with a bottom made of Mylar film 3–5 µm thick. During X-ray fluorescence spectral analysis, Olympus VANTA C equipment manufactured in the United States and a Shimadzu EDX 7000P analyzer manufactured in Japan were used.

2.4. Quality Assurance and Analytical Quality Control

Instrument calibration was performed before analytical measurements using certified reference materials (CRMs) for soils and geological materials with known concentrations of the target analytes in accordance with the corresponding GOST and ST RK analytical standards. Calibration performance was periodically verified throughout the analytical sequence. Internal quality-control procedures included routine calibration verification, analysis of certified reference materials, duplicate measurements of selected samples, and continuous monitoring of instrumental stability. Sample preparation, storage, and analytical procedures followed the requirements of ISO/IEC 17025 and the relevant national analytical standards. The analytical methods were applied within the validated working ranges specified in the corresponding analytical standards. Results below the analytical detection limit were considered non-detectable and were excluded from subsequent statistical analyses. Analytical precision and repeatability complied with the metrological performance requirements established for the applied analytical methods.

2.5. Study of Radionuclide Activity Indicators

Soil and ground samples collected for the control of physicochemical indicators were simultaneously analyzed for gamma-radionuclide activity. Separate samples were taken for measurement with consideration of the soil horizon or layer. To assess gamma-radionuclide activity, an RKG-AT1320C gamma radiometer was used. This instrument is designed to measure the volumetric activity and specific activity of gamma-emitting radionuclides, including ^{131}I, ^{134}Cs, ^{137}Cs, ^{40}K, ^{226}Ra, and ^{232}Th, in water, food products, feed, soil, construction materials, industrial raw materials, and other environmental objects. The RKG-AT1320C gamma radiometer provides automatic identification of the radionuclide composition of a sample and selection from among specified compositions for subsequent activity calculation. Atomtech manufactured the instrument in Belarus. During data processing and statistical analysis of measurement results, the recommendations of interstate standards were followed (Federal Agency for Technical Regulation and Metrology, 2011, 2019).

2.6. Statistical Analysis

Statistical analyses were conducted using IBM SPSS Statistics version 32.0 (IBM Corp., Armonk, NY, USA). Descriptive statistics were calculated for all vegetation, soil, and radionuclide variables. Continuous variables are reported as the mean ± standard deviation (SD), median, minimum, and maximum values, as appropriate, whereas categorical variables are presented as frequencies and percentages. We assessed data normality using the Shapiro–Wilk test, complemented by visual examination of histograms and normal Q–Q plots. As several variables deviated from a normal distribution, associations among soil physicochemical properties, mobile and total elemental concentrations, sampling depth and gamma-radionuclide activity were evaluated using Spearman's rank correlation coefficient (ρ), a non-parametric measure of association. All statistical tests were two-tailed, and differences were considered statistically significant at $p<0.05$. Correlation coefficients were interpreted according to their strength and direction. Missing data were excluded only from the respective analyses in which they occurred. Because the primary objective of this study was to characterize early post-fire vegetation succession and associated soil properties rather than to classify observations or develop predictive models, multivariate statistical analyses were not performed.

3. RESULTS

3.1. Studies of Control Plots: Characteristics of Plant Community Formation

3.1.1. Control-1: Control-1 represented an undisturbed Pinus sylvestris forest (stand formula 10P, stand density 0.4, age 60–80 years) with vegetation typical of steppe pine forests on sandy soils (Fig. 3). The herbaceous layer was dominated by Calamagrostis epigeios, Festuca valesiaca, Carex supina, and Artemisia austriaca. Species richness increased from 24 species in 2023 to 33 species in 2024 (Table 1), whereas total projective cover remained relatively stable (40–50%). Despite the increase in species richness, the floristic composition and overall community structure remained largely unchanged throughout the study period. Characteristic steppe pine forest species persisted at low abundance, whereas dominant species maintained high constancy. Anthropogenic disturbance remained low (digression stage IV), with only 10–15% disturbance of the herbaceous layer. The synanthropization coefficient remained very low (3.4%), while total species activity increased only slightly from 171.7% in 2023 to 177.2% in 2024 (Table 2), indicating a stable and well-preserved plant community.

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Fig. 3: Semiozernoye Forestry Institution, Kalininskoye Forestry, compartment 121, subcompartment 24, Control-1. A — 2023; B — 2024.

Table 1: Floristic indicators of the pine forest in Control-1, Semiozernoye Forestry Institution, Kalininskoye Forestry (n = 10)

Plant species	P*	V*	A*	CC*
2023				
Calamagrostis epigeios (L.) Roth	15.8	100	39.7	V
Festuca valesiaca Gaud.	4.65	70	18	IV
Carex supina Willd. ex Wahlenb.	15	60	30	III
Artemisia austriaca Jacq.	2.85	60	13.1	III
Stipa pennata L.	3.1	50	12.4	III
Asparagus pallasii Miscz.	0.25	50	3.5	III
2024				
Calamagrostis epigeios (L.) Roth	10.55	100	32.5	V
Carex supina Willd. ex Wahlenb.	9.5	100	30.8	V
Festuca valesiaca Gaud.	9.1	100	30.2	V
Medicago falcata L.	1.65	90	12.2	V
Poa pratensis L.	1.55	70	10.4	IV

Table 2: Main indicators at the monitoring site in the Semiozernoye Forestry Institution, Kalininskoye Forestry

Indicators	Control		Burned area	
	2023	2024	2023	2024
Density of pine stands, score	0.4	0.4	0	0
TPC,%	50	40	16.6	50
Number of species, pcs.	24	33	29	35
Including weed species, pcs.	3	3	5	9
Synanthropization coefficient,%	9	3.4	13.3	25.7
Total species activity,%	171.7	177.2	70.6	228.5
Including weed species	7.5	2.6	3.8	45.6
Share of weed species activity,%	4.4	2.0	5.4	20.0

3.1.2. Burned Area-1 (Semiozernoye Forestry Institution, Kalininskoye Forestry, compartment 121; 52.409356, 64.208874): Burned Area-1 exhibited pronounced post-fire vegetation changes. Total projective cover increased from 16% in 2023 to 50% in 2024, while species richness increased from 29 to 35 species (Fig. 4). During the first post-fire growing season, vegetation was composed primarily of species regenerating from protected belowground organs, whereas most species exhibited low constancy. By the second year, the community was dominated by Calamagrostis epigeios, Carex supina, and Chenopodium album, accompanied by a substantial expansion of ruderal and synanthropic species (Table 3). Total species activity increased approximately 1.5-fold, primarily reflecting the rapid establishment and spread of weed species. The number of weed species increased from five to nine, while the synanthropization coefficient nearly doubled from 13.3% to 25.7% (Table 2). The site remained at anthropogenic digression stage V, with approximately 70% disturbance of the herbaceous layer, indicating that vegetation recovery was still dominated by early-successional opportunistic species.

3.1.3. Control-2 (Semiozernoye Forestry Institution, Novonezhinskoye Forestry, compartment 20, subcompartment 1; 52.505632, 64.069678): Control-2 represented an undisturbed pine forest (stand formula 9P1As, stand density 0.4–0.5, age 60–90 years) with a well-preserved vegetation structure characteristic of steppe pine ecosystems (Fig. 5). The herbaceous layer was dominated by Calamagrostis epigeios, Carex supina, Festuca valesiaca, and Glycyrrhiza uralensis. Species richness remained nearly constant between years (29 species in 2023 and 30 species in 2024), although total projective cover decreased from 61.0% to 44.5%. Only minor temporal variation in phytocoenosis structure was observed during the study period (Table 4), indicating a stable vegetation community. Anthropogenic disturbance remained low (digression stage IV), with 10–15% disturbance of the herbaceous layer. Although the synanthropization coefficient increased from 5.7% to 13.3%, total species activity remained relatively stable (205% in 2023 and 189% in 2024; Table 5), suggesting that the overall community structure was maintained.

3.1.4. Burned Area-2 (Semiozernoye Forestry Institution, Novonezhinskoye Forestry, compartment 72, subcompartment 22; 52.47174, 64.09628): Burned Area-2 was affected by a combined fire. Total projective cover increased from 17% in 2023 to more than 60% in 2024, while species richness increased from 27 to 38 species (Fig. 6). During the first post-fire growing season, the vegetation was dominated by Calamagrostis epigeios, whereas most other species occurred with low constancy (Table 5). In the second year, Calamagrostis epigeios and Chamerion angustifolium, a characteristic post-fire colonizer, became the dominant species, accompanied by a marked increase in ruderal taxa, including Lactuca serriola, Conyza canadensis, and Chenopodium album. The number of weed species more than doubled (from four to nine), the synanthropization coefficient increased from 12.9% to 22.5%, and the proportion of weed species activity increased from 11.6 to 18.3% (Table 7). The site remained at anthropogenic digression stage V, with approximately 70% disturbance of the herbaceous layer, indicating that vegetation development was still in the early stages of post-fire succession.

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Table 3: Floristic indicators of the pine forest in the burned area, Semiozernoye Forestry Institution, Kalininskoye Forestry (n = 10)

Plant species	P	V	A	CC
2023				
Calamagrostis epigeios (L.) Roth	5	30	12.2	II
Galium verum L	1.35	30	6.4	II
2024				
Calamagrostis epigeios (L.) Roth	5.9	100	24.3	V
Carex supina Willd. ex Wahlenb.	60	100	77.5	V
Chenopodium album L.	6.75	90	24.6	V
Festuca valesiaca Gaud.	3.8	80	17.4	IV
Conyza canadensis (L.) Cronquist.	1.2	70	9.2	IV

Fig. 4: Semiozernoye Forestry Institution, Kalininskoye Forestry, compartment 121, subcompartment 24, Burned Area-1.

Table 4: Floristic indicators of the pine forest in Control-2, Semiozernoye Forestry Institution, Novonezhinskoye Forestry (n = 10)

Plant species	P	V	A	CC
2023				
Calamagrostis epigeios (L.) Roth	13.5	100	36.7	V
Carex supina Willd. ex Wahlenb.	13	80	32.2	V
Festuca valesiaca Gaud.	5	70	18.7	IV
Allium lineare L.	0.7	50	5.9	III
Cerasus besseyi L.H. Bailey	3.1	50	12.4	III
Cotoneaster melanocarpus Fisch. ex Blytt.	6.1	50	17.5	III
2024				
Calamagrostis epigeios (L.) Roth	13.5	100	36.74	V
Carex supina Willd. ex Wahlenb.	13	80	32.25	V
Festuca valesiaca Gaud.	5	70	18.71	IV
Cotoneaster melanocarpus Fisch. ex Blytt.	6.1	50	17.46	III
Cerasus besseyi L.H. Bailey	3.1	50	12.45	III
Allium lineare L.	0.7	50	5.92	III

Fig. 5: Semiozernoye Forestry Institution, Novonezhinskoye Forestry, compartment 20, subcompartment 1, control.

Table 5: Floristic indicators of the pine forest in Burned Area-2, Semiozernoye Forestry Institution, Novonezhinskoye Forestry (n = 10)

Plant species	P	V	A	CC
2023				
Calamagrostis epigeios (L.) Roth	13.9	90	35.4	V
Melilotus albus Medik.	0.45	60	5.2	III
Carex supina Willd. ex Wahlenb.	0.95	40	6.2	II
2024				
Calamagrostis epigeios (L.) Roth	43	100	65.6	V
Chamerion angustifolium (L.) Holub	2.45	100	15.7	V
Lactuca serriola L.	1.95	80	12.5	IV
Conyza canadensis (L.) Cronquist.	1.6	80	11.3	IV
Phragmites australis (Cav.) Trin. ex Steud.	1.3	60	8.8	III
Chenopodium album L.	0.55	60	5.7	III
Carex supina Willd. ex Wahlenb.	2.15	50	10.4	III
Seseli libanotis (L.) W. D. J. Koch	0.7	50	5.9	III
Silene nutans L.	0.35	50	4.2	III

Fig. 6: Semiozernoye Forestry Institution, Novonezhinskoye Forestry, compartment 72, subcompartment 22, Burned Area-2.

3.1.5. Cleared Burned Area (Semiozernoye Forestry Institution, Novonezhinskoye Forestry, compartment 42; 52.47554, 64.08967): The Cleared Burned Area underwent post-fire logging during May–June 2023, resulting in a vegetation recovery trajectory distinct from that observed in the uncleared burned sites. Total projective cover increased from 29.0% in 2023 to 60.6% in 2024 (Fig. 7), whereas species richness declined from 55 to 40 species. The first post-fire year was characterized by high floristic richness, including numerous psammophytic steppe species together with synanthropic taxa (Table 6). By 2024, the community had shifted toward the dominance of steppe species, particularly Agropyron cristatum and Gypsophila paniculata, while ruderal species such as Lactuca serriola, Conyza canadensis, and Chenopodium album remained abundant. Total species activity remained relatively stable (198.0–206.7%), whereas the synanthropization coefficient increased markedly from 14.5% to 29.7%, indicating continued anthropogenic transformation of the vegetation. The site remained at anthropogenic digression stage V, with approximately 60% disturbance of the herbaceous layer.

Table 6: Floristic indicators of the pine forest in the cleared burned area, Semiozernoye Forestry Institution, Novonezhinskoye Forestry (n = 10)

Plant species	P	V	A	КП
2023				
Calamagrostis epigeios (L.) Roth	3.45	90	17.6	V
Chenopodium album L.	8.8	90	28.1	V
Achillea millefolium L.	1.35	60	9	III
Astragalus scoparius Schrenk	0.45	60	5.2	III
Cerasus besseyi L.H. Bailey	2.7	60	12.7	III
2024				
Agropyron cristatum (L.) Beauv.	27.5	100	52.4	V
Gypsophila paniculata L.	4.7	90	20.6	V
Chenopodium album L.	2.55	70	13.4	IV
Festuca valesiaca Gaud.	5.8	60	18.7	III
Stipa pennata L.	3.7	60	14.9	III
Galium verum L	1.55	60	9.6	III
Berteroa incana (L.) DC.	0.4	60	4.9	III
Glycyrrhiza uralensis Fisch.	0.35	60	4.6	III
Chenopodium glaucum L.	1.35	50	8.2	III

Table 7: Main indicators at the monitoring site of the Semiozernoye Forestry Institution, Novonezhinskoye Forestry

Indicators	Control		Burned area		Cleared Burned Area	
	2023	2024	2023	2024	2023	2024
Density of pine stands, score	04-05	04-05				
TPC,%	61	44.5	17	60.5	29	60.6
Number of species, pcs.	29	30	27	38	55	40
Including weed species, pcs.	2	4	4	9	8	11
Synanthropization coefficient,%	5.7	13.3	12.9	22.5	14.5	29.7
Total species activity,%	205	189	68.1	193.4	198.0	206.7
Including weed species	2.4	4.9	7.9	35.4	46.5	44.3
Share of weed species activity,%	1.1	2.6	11.6	18.3	23.5	21.5

Fig. 7: Semiozernoye Forestry Institution, Novonezhinskoye Forestry, cleared burned area, compartment 42: A — 2023; B — 2024.

3.1.6. Characteristics of Plant Community Formation Across All Studied Plots: Across all burned sites, post-fire vegetation recovery followed two principal successional pathways. The first involved the persistence and regeneration of fire-tolerant (pyrophytic) perennial species, including Calamagrostis epigeios, Carex supina, Festuca valesiaca, Artemisia austriaca, and Stipa pennata, which survived the fire through protected belowground organs. The second pathway was characterized by rapid colonization of disturbed habitats by opportunistic (explerent) species, primarily synanthropic taxa such as Chenopodium album, Conyza canadensis, Lactuca serriola, and Taraxacum officinale. Vegetation recovery differed substantially between burned forest stands and cleared burned areas. Burned forest plots exhibited relatively gradual recovery dominated by pyrophytic species, whereas cleared sites experienced rapid

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colonization by synanthropic and meadow-steppe species following post-fire logging. Consequently, cleared areas maintained higher species richness during the initial post-fire year but exhibited a more pronounced increase in synanthropization during the second year, reflecting stronger anthropogenic influence on vegetation succession.

3.2. Study of Soil Quality Indicators

3.2.1. Morphological Characteristics of Soils in the Studied Plots of Kalininskoye Forestry: The morphological characteristics of soils in the study plots of Kalininskoye Forestry were evaluated based on detailed field observations. Soil profile descriptions and diagnostic morphological features are presented in Tables 8 and 9.

Table 8: Structure of the upper soil layers in forest plots unaffected by fire

Horizon (layer)	Soil sample numbers 1	2	3
A_0	0–3 cm; litter of needles, twigs, and cones	0–2 cm; litter of needles, twigs, cones, decomposed from below	0–2 cm; litter of needles, twigs, and cones
A_I	3–6 cm; weakly humified, dark-gray layer penetrated by plant roots	2–7 cm; humified, dark-brown transitional layer penetrated by plant roots	2–10 cm; humified, dark-brown layer, turning grayish when drying, penetrated by plant roots
A–B	7–10 cm; slightly moist, dark-gray, compacted, with inclusions of dark spots from A1	7–12 cm; dry, dark-gray, sandy loam	10–20 cm; dry, dark-gray, compacted
B	10–20 cm; light-gray sand with thin brown interlayers	12–25 cm; light-gray sand with a darkish tint	20–30 cm; light-gray sand with thin brown interlayers
C	Deeper than 20 cm; yellowish-gray sand	Deeper than 25 cm; yellowish-gray sand	Deeper than 30 cm; yellowish-gray sand

Table 9: Structure of the upper soil layers in burned forest plots. Cleared burned area

Horizon (layer)	Soil sample numbers 1	2	3
A_0	0–1.0 cm; freshly fallen litter of brown needles and burned twigs	0–0.5 cm; freshly fallen litter of brown needles and burned twigs	0–0.5 cm; freshly fallen litter of brown needles and burned twigs
A_I	1–2 cm; black layer of charcoal particles	0–2 cm; dark layer of charcoal particles	0–3 cm; completely burned out
A–B	2–6 cm; yellow-orange spots of burned organic matter with dark-gray soil spots	2–5 cm; dark-brown layer with yellow-orange spots of burned organic matter	3–6 cm; yellow-orange spots of burned organic matter with dark-gray soil spots
B	7–20 cm; very dark layer with black and orange spots	6–10 cm; black, locally dark-gray sand	7–12 cm; black, locally dark-gray sand
C	Deeper than 20 cm; yellowish-gray sand with dark streaks	Deeper than 10 cm; yellowish-gray sand with dark streaks	Deeper than 12 cm; yellowish-gray sand with dark streaks

3.2.2. Morphological Characteristics of Soils in the Studied Plots of Novonezhinskoye Forestry: The morphological characteristics of soils in the study plots of Novonezhinskoye Forestry were similarly assessed through field investigations. The corresponding soil profile descriptions and morphological characteristics are presented in Tables 10–12. Soil samples were collected from representative soil horizons across all study plots to determine the concentrations of mobile and total forms of selected soil quality indicators (Appendices 1–4). Overall, the investigated soils were alkaline and generally characterized by low concentrations of humus, nitrate nitrogen, available phosphorus, and exchangeable potassium. Humus content in the upper and subsurface horizons corresponded to the low-humus category according to standard agrochemical classification criteria. Nitrate nitrogen concentrations were generally below 10 mg kg^{-1}, whereas available phosphorus and exchangeable potassium were predominantly below 50 mg kg^{-1}.

Despite the relatively low nutrient status, the concentrations of mobile forms of potentially toxic elements, including Pb, Cr, Ni, Cu, Mn, Cd, and Zn, remained below the established environmental guideline values. Likewise, the total concentrations of heavy metals and other potentially hazardous elements did not exceed the corresponding maximum permissible concentrations, indicating the absence of significant soil contamination. Spearman's rank correlation analysis identified several significant relationships among soil quality indicators. Sampling depth exhibited strong negative correlations with soil moisture content and the mobile concentrations of Cd, Mn, Zn, and Pb ($\rho = -0.48$ to -0.93), indicating a progressive decline in these variables with increasing soil depth. Humus content was positively correlated with exchangeable potassium, nitrate nitrogen, cadmium, and lead, suggesting the important role of soil organic matter in nutrient retention and trace element accumulation. Exchangeable potassium also showed positive correlations with available phosphorus, nitrate nitrogen, Cd, Mn, and Zn. Among the trace elements, particularly strong positive associations were observed between Cd and Mn, Cr and Mn, and Zn and Mn, reflecting their similar geochemical behavior within the soil matrix. Analysis of the total elemental composition demonstrated that the mineral fraction of the soils was dominated by silicon, aluminum, titanium, iron, and calcium oxides. Strong positive correlations were identified among several major and trace elements, including Si–Nb, Si–K, K–Al, K–Ti, Mn–Fe, Fe–Zn, Fe–Pb, Zn–Ni, and Sr–Ca (Appendix 4), indicating common mineralogical associations and geochemical processes governing elemental distribution in the studied soils.

Table 10: Structure of the upper soil layers in forest plots unaffected by fire

Horizon (layer)	Soil sample numbers 1	2	3
A_0	0–2 cm; litter of needles, twigs, and cones	0–6 cm; thick litter of needles, twigs, and cones, decomposed from below	0–4 cm; litter of needles, twigs, and cones
A_I	2–5 cm; weakly humified, dark-brown layer, turning grayish when drying, penetrated by plant roots	6–10 cm; humified, dark-brown layer, turning grayish when drying, penetrated by plant roots	4–10 cm; humified, dark-brown layer, turning grayish when drying, penetrated by plant roots
A–B	5–15 cm; slightly moist, dark-gray, compacted, with inclusions of dark spots from A1	10–17 cm; dry, dark-gray, compacted	10–20 cm; dry, dark-gray, compacted
B	15–20 cm; light-gray sand with thin brown interlayers	17–25 cm; light-gray sand with a darkish tint	20–30 cm; light-gray sand with thin brown interlayers
C	Deeper than 20 cm; yellowish-gray sand	Deeper than 25 cm; yellowish-gray sand	Deeper than 30 cm; yellowish-gray sand

Table 11: Structure of the upper soil layers in burned forest plots. Cleared burned area.

Horizon (layer)	Soil sample numbers 1	2	3
A_0	0–0.5 cm; freshly fallen litter of brown needles and burned twigs	0–0.5 cm; freshly fallen litter of brown needles and burned twigs	0–0.5 cm; freshly fallen litter of brown needles and burned twigs
A_I	1–2 cm; black layer of charcoal particles	0–1 cm; dark layer of charcoal particles	0–2 cm; completely burned out
A–B	2–6 cm; yellow-orange spots of burned organic matter with dark-gray soil spots	1–4 cm; yellow-orange spots of burned organic matter with dark-gray soil spots	2–10 cm; yellow-orange spots of burned organic matter with dark-gray soil spots
B	6–20 cm; very dark layer with black and orange spots	4–8 cm; black, locally dark-gray sand	10–20 cm; black, locally dark-gray sand
C	Deeper than 20 cm; yellowish-gray sand with dark streaks	Deeper than 8 cm; yellowish-gray sand with dark streaks	Deeper than 20 cm; yellowish-gray sand with dark streaks

Table 12: Structure of the upper soil layers in burned forest plots cleared of burned wood. Cleared burned area.

Horizon (layer)	Soil sample numbers 1	2	3
A_0	0–0.5 cm; freshly fallen litter of brown needles and burned twigs	0–0.5 cm; freshly fallen litter of brown needles and burned twigs	0–0.5 cm; freshly fallen litter of brown needles and burned twigs
A_I–A–B	0–10 cm; unstructured horizon with yellow-orange spots of burned-out organic matter, mixed with dark-gray soil during forest clearing and logging, with inclusions of charcoal particles	0–10 cm; unstructured horizon with yellow-orange spots of burned-out organic matter, mixed with dark-gray soil during forest clearing and logging, with inclusions of charcoal particles	0–15 cm; unstructured horizon with yellow-orange spots of burned-out organic matter, mixed with dark-gray soil during forest clearing and logging, with inclusions of charcoal particles
B	10–20 cm; dark-gray sand	10–20 cm; dark-gray sand	15–30 cm; dark-gray sand
C	Deeper than 20 cm; yellowish-gray sand	Deeper than 20 cm; yellowish-gray sand	Deeper than 30 cm; yellowish-gray sand

Table 13: Correlations between gamma-radionuclide activity and layer depth

	Cs137	40K
40K	0.53	
Layer	-0.77	-0.45

3.3. Studies of Gamma-Radionuclide Activity in Ground Sample Specimens

Appendix 3 presents the values of gamma-radionuclide activity indicators in soil sample specimens. Activities of all detected radionuclides remained below the maximum permissible levels established by Russian and Kazakh regulations (Chief State Sanitary Doctor of the Russian Federation, 2009; Ministry of Health of the Republic of Kazakhstan, 2022). Among the analysed radionuclides, ^{40}K and ^{137}Cs were consistently detected in almost all samples, whereas the technogenic radionuclide ^{134}Cs occurred only sporadically. The highest ^{137}Cs activity was recorded in the upper soil horizons, and the activities of both ^{40}K and ^{137}Cs decreased with increasing soil depth and layer density (Table 13; Appendix 3). A significant positive correlation was observed between the activities of ^{40}K and ^{137}Cs, indicating similar patterns of vertical distribution within the soil profile. Overall, the radionuclide data indicate a stable radiological status of the study sites, with radionuclide activities remaining within regulatory limits and exhibiting the expected concentration in surface soil layers.

4. DISCUSSION

4.1. Mechanisms Driving Post-fire Vegetation Changes in the Amankaragai Island Pine Forest

Two findings dominate the post-fire vegetation recovery documented in Sections 3.1.2, 3.1.4 and 3.1.5. First, *Calamagrostis epigeios* Roth, already present as a co-dominant in both Control-1 (projective cover 15.8% in 2023) and Control-2 (projective cover 13.5% in 2023) (Table 1 and 4), became the dominant species in every burned plot, reaching 24.3% cover in Burned Area-1, 65.6% in Burned Area-2, and contributing substantially to recovery in the cleared site (Tables 3, 5 and 6). Second, the burned and cleared burned plots accumulated ruderal and meadow-steppe species at the expense of typical forest-floor forbs: weed-species number increased from 5 to 9, from 4 to 9, and from 8 to 11 (cleared burned area), with the synanthropization coefficient following the same direction (13.3 → 25.7%, 12.9 → 22.5%, 14.5 → 29.7%) (Table 2 and 7). These two lines of evidence are biologically coherent. *C. epigeios* is a long-rhizomatous, high-morphological-plasticity grass whose renewal buds lie at 6–10 cm depth, well below the soil thermal front of typical surface and crown fires, which explains both its recurring dominance in the island pine forests and its rapid post-fire takeover at all our sites (Sultangazina et al., 2025). The same life-history trait has been documented in temperate European meadows, where *C. epigeios* generates a "particularly dense and thick litter that prevents the germination of other species" and produces "long-lasting stable grassland communities, stopping the course of succession" (Pruchniewicz & Żołnierz, 2017). This mechanism is particularly concerning in our case because *Pinus sylvestris* is an obligate seeder that requires a mineral, competition-free seedbed; dense *C. epigeios* litter can therefore suppress pine regeneration for decades — a parallel to the well-described inhibition of white spruce (*Picea glauca*) by the closely related *Calamagrostis canadensis* in post-fire boreal stands of North America (Lieffers et al., 1993; Cater & Chapin, 2000).

A second non-trivial observation concerns the divergence between uncleared burned stands and the cleared burned area. In Burned Area-2, floristic richness rose from 27 to 38 species and projective cover from 17% to 60.5%, with *C. epigeios* + *Chamerion angustifolium* + *Lactuca serriola* dominating (Table 5). In the cleared burned plot, floristic richness declined from 55 to 40 species in the second year, projective cover rose from 29% to 60.6%, and the community shifted to *Agropyron cristatum–Gypsophila paniculata–Festuca valesiaca* steppe grassland with persistent *Chenopodium album*, *Lactuca serriola* and *Conyza canadensis* synanthropes (Table 6). The synanthropization coefficient reached 29.7% in the cleared plot, which is almost double the value in the uncleared burned area, and the share of weed-species activity remained above 20% throughout (Table 7). The ecological significance of this divergence is twofold. First, it confirms the strong negative effect of post-fire salvage logging on natural pine regeneration that has been reported in dry Scots pine stands elsewhere, where only 16 years after a stand-replacing fire and salvage-logging combination is natural *Pinus sylvestris* regeneration still insufficient (Mantero et al., 2023). Second, it provides empirical support from the southern margin of the Scots pine range for the general Siberian finding that "dry pine stands and repeatedly disturbed forests were the most vulnerable to experience a biome shift during regeneration toward steppe vegetation" (Blumroeder et al., 2022). None of the burned plots in the present study contained a single *P. sylvestris* seedling of any height class, an outcome consistent with the regional assessment that natural pine regeneration requires not only the absence of dense *C. epigeios* cover but also active silvicultural treatment (Lyavdanskaya et al., 2025; Sultangazina et al., 2025).

The co-occurrence in our burned plots of typical forest species (re-sprouting from belowground organs, e.g., *Carex supina*, *Festuca valesiaca*, *Stipa pennata*) with ruderal explerents (*Chenopodium album*, *Conyza canadensis*, *Lactuca serriola*, *Taraxacum officinale*) is the signature pattern described for secondary pyrogenic successions over the past century and remains broadly consistent with recent boreal and temperate case studies, where stand age, fire severity, residual seedbank and post-fire climate jointly shape trajectories (Clements, 1916, 1928; Dawe et al., 2022; Day et al., 2023).

4.2. Fire-induced Changes in Soil Morphology and Chemistry and the Soil's Role as a Recovery Substrate

The morphological data summarized in Table 8–12 show that the A0 and A1 horizons, typically 5–10 cm thick in undisturbed stands, were reduced to charcoal layers of 0.5–3 cm or completely burned out in the burned plots. This loss is the principal mechanism by which wildfire modifies the early-stage ecosystem in our sandy soils: the organic-rich surface layer that drives cation exchange, water retention and seedling anchoring is replaced by a thin, hydrophobic ash–charcoal veneer. The dichotomy between cleared and uncleared burned plots is also striking at the horizon level: cleared sites contain an "unstructured" 10–15 cm A1–A–B horizon of mixed charcoal, burnt organic matter, and re-deposited mineral soil—a marked mechanical disturbance that further reduces seedbed suitability.

The chemical profile of the upper horizons nevertheless remained within functional limits. The humus content (0.19–1.95%) corresponds to the "low-humus" category used by the Russian TsINAO classification; nitrate nitrogen was mostly <40 mg/kg, mobile phosphorus <50 mg/kg, and mobile potassium low; extractable lead, chromium, nickel, copper, manganese, cadmium, zinc, cobalt and arsenic were below their respective MPCs/APC values in every sample. These findings align directly with current international evidence showing that, in forest settings, mature sandy soils mineral substrates can buffer the chemical impact of fire on the rooting zone, while the organic-rich A0/A1 is the horizon most vulnerable to loss (Buts et al., 2022; Nureev, 2025).

The correlation analyses (Appendices 4.1 and 4.2) refine this interpretation. The strong negative correlations of sampling depth with Cd, Mn, Zn and Pb (r ≈ −0.48 to −0.93) and the positive correlations among humus, potassium, nitrates and trace elements indicate that biological activity and trace-element retention are concentrated in the upper few centimeters — exactly the horizon most affected by fire. The strong mutual correlations among major oxides (Si–Nb, K–Al, K–Ti, Mn–Fe, Fe–Zn, Fe–Pb, Zn–Ni, Sr–Ca) indicate that the mineral matrix of these sandy soils is inherited and fire-stable: the loss of organic matter does not translate into a major perturbation of the underlying geochemistry. This decoupling of organic from mineral horizons is an important point for restoration planning: it implies that any active restoration effort on these sites should target the top few centimetres first, primarily by rebuilding a humus-retaining organic cover and by suppressing the meadow-steppe grass layer that we have shown effectively colonizes these surfaces (Alayan et al., 2022; Lindenmayer et al., 2022).

The interpretation of these findings in a 2020–2025 context harmonises with recent work in Mediterranean and temperate pine stands showing that moderate-to-severe *P. sylvestris* fires typically reduce OC and N in the surface horizon but rarely push bulk soil trace elements above regulatory limits; that site-precise rather than uniform restoration is most effective; and that, even 30 years after post-fire afforestation, near-natural podzol morphology with humus horizons comparable to primary-succession post-mining sites can be re-established (Józefowska et al., 2023; Mantero et al., 2024).

4.3. Nutrient Cycling in the Upper Horizons of Post-fire Island Pine Soils

The agrochemical profile of the Amankaragai soils reflects the nutrient-poor character of sandy island pine ecosystems while revealing characteristic post-fire redistribution processes. Low humus content, low nitrate nitrogen, low mobile phosphorus and potassium, alkaline reaction, and concentrations of mobile trace elements below regulatory limits indicate that wildfire altered nutrient availability without causing long-term soil contamination. The strongest depth-related correlations suggest a clear separation between the organic and mineral components of the soil profile. Mobile nutrients and trace elements accumulated mainly within the upper few centimetres, whereas the deeper sandy substrate contributed relatively little to nutrient retention. Similar post-fire redistribution of nutrients has been widely reported, where ash deposition increases the availability of exchangeable cations and mineral nutrients within surface horizons (Agbeshie et al., 2022).

The observed relationship between low nitrate concentrations and relatively higher phosphorus availability also resembles the fire-induced N:P imbalance described in other post-fire forest ecosystems (Eckdahl et al., 2024; Shen et al., 2024). Although nutrient enrichment in Amankaragai was considerably weaker because of the coarse sandy substrate and semi-arid climate, the direction of post-fire nutrient redistribution was consistent with these international observations. Finally, the strong correlations among the major rock-forming oxides confirm that the geochemical composition of the mineral substrate remained essentially unchanged after fire, supporting previous findings for post-fire Scots pine ecosystems (Woś et al., 2025).

4.4. Organic Matter Recovery, Ash Dynamics and the Soil Surface as a Driver of Succession

The disappearance of the A0/A1 horizon and its replacement by a thin charcoal layer represent the most important pedological consequence of the 2022 wildfire. Under the dry climatic conditions of Northern Kazakhstan, this loss is particularly significant because the organic surface horizon functions as the principal reservoir for water retention, cation exchange, and seedling establishment. International studies consistently indicate that recovery of this horizon requires many years or even decades. Mediterranean pine forests generally require 2–3 years before measurable recovery of microbial activity and soil organic matter begins (Rodríguez et al., 2018), whereas semi-arid Pinus halepensis ecosystems require approximately 15–21 years for substantial restoration of plant–soil interactions (Moya et al., 2019). In temperate Scots pine forests, recovery of soil organic carbon may require around 30 years (Woś et al., 2025), while complete redevelopment of humus horizons on sandy substrates may continue for nearly a century (Gus-Stolarczyk & Drewnik, 2017). Similar long-term recovery of Podzol development after post-fire afforestation has also been demonstrated by Józefowska et al. (2023). These studies indicate that restoration of the Amankaragai pine forest should primarily focus on accelerating recovery of the organic surface layer rather than attempting rapid nutrient supplementation, while simultaneously limiting competition from dense Calamagrostis epigeios stands that may delay tree regeneration.

4.5. Post-fire Soil Development and the Long-term Pedogenic Trajectory of Amankaragai

Taken together, the vegetation, morphological and agrochemical results indicate that post-fire ecosystem recovery in the Amankaragai pine forest is controlled primarily by restoration of the upper organic horizon rather than by changes in the mineral substrate. The deeper sandy profile retained its characteristic geochemical composition, whereas the A0/A1 horizon preserved the principal signature of fire disturbance, corresponding to the concept of "pedological memory" proposed by Phillips & Marion (2003). Accordingly, successful restoration

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should prioritize rebuilding the litter and humus horizons, reducing competition from Calamagrostis epigeios, and avoiding intensive post-fire salvage logging that further disturbs the already degraded surface layer. Such an approach is consistent with current international recommendations emphasizing ecosystem-specific restoration strategies for post-fire pine forests (Alayan et al., 2022; Lindenmayer et al., 2022; Mantero et al., 2023).

4.6. Restoration, Climate-change and Management Implications

The combined vegetation and soil evidence has three direct implications for restoration of the Amankaragai pine forest. First, retention of burned stands appears more favourable for natural recovery than post-fire salvage logging, because surviving belowground organs and residual organic horizons provide a better substrate for regeneration (Lindenmayer et al., 2022; Sultangazina et al., 2025). Second, active restoration measures should reduce competition from dense Calamagrostis epigeios cover by creating mineral-soil microsites suitable for pine establishment, consistent with recommendations developed for other Calamagrostis-dominated pine systems (Lieffers et al., 1993; Mantero et al., 2024). Third, the radionuclide data indicate a stable radiological background, with activities below MPC values and radionuclides concentrated mainly in the organic-rich upper horizons, suggesting that recent fire did not cause substantial downward migration of radiocaesium.

These management implications should be considered within the broader context of increasing wildfire activity under climate change. Boreal and high-latitude forest fires during the 2023–2024 season released emissions approximately 16% above the multi-year average, with some regions exceeding historical means by more than ninefold (Jones et al., 2024) and larger fires have been shown to intensify post-fire land-surface warming (Zhao et al., 2024). The September 2022 fires that affected 33,824 ha of forest land in Kostanay Region form part of this wider trend of increasing fire activity (Jones et al., 2022; Senande-Rivera et al., 2022). Without site-specific restoration measures that maintain surviving pyrophytes and limit competitive grass dominance, dry island pine forests of Northern Kazakhstan may remain vulnerable to long-term conversion toward steppe vegetation, as documented for disturbed pine ecosystems of southern Siberia (Blumroeder et al., 2022).

4.7. Ecological Significance of the Gamma-radionuclide Activity Recorded in the Upper Soil Layers of the Amankaragai Pine Forest

The gamma-spectrometric data indicate that the radiological status of the Amankaragai island pine forest remained stable one year after the September 2022 fires. Activities of natural radionuclides (^{40}K, ^{226}Ra and ^{232}Th) and technogenic ^{137}Cs remained below the regulatory maximum permissible concentrations adopted by Kazakhstan and the Russian Federation (Chief State Sanitary Doctor of the Russian Federation, 2009; Ministry of Health of the Republic of Kazakhstan, 2022).

The main ecological signal is the strong concentration of ^{137}Cs in the organic-enriched upper horizons and its marked decline with depth. The negative relationship between ^{137}Cs activity and soil-layer depth ($r = -0.77$) indicates that most mobile radiocaesium remains within the first few centimetres of these sandy soils, while the positive correlation with ^{40}K activity ($r = 0.53$) suggests a common retention mechanism associated with the surface organic horizon. The detection of short-lived ^{134}Cs in only a few deeper subsurface samples is consistent with the long-term burial of the original Chernobyl-derived fallout signal beneath accumulating litter, a pattern previously documented in mature Scots pine forests of the Chernobyl region (Dolgushin et al., 2020; Dolgushin & Korobova, 2021; Ramzaev et al., 2023).

4.8. Comparison with Previous Forest Radionuclide Studies

The depth-concentrated distribution of ^{137}Cs observed in the Amankaragai pine forest closely matches patterns described for Pinus sylvestris stands in the Chernobyl Exclusion Zone and adjacent regions, where radionuclides remain largely retained within the upper soil profile despite gradual downward redistribution through bioturbation and illuviation (Holiaka et al., 2020). Long-term monitoring of Belarusian pine forests similarly demonstrates a progressive decline in external γ-radiation dose rates as short-lived radionuclides decay and ^{137}Cs is redistributed within surface horizons (Perevolotskaya, 2025). The Amankaragai values are substantially lower than those reported from contaminated Chernobyl sites, yet the same conceptual model applies: a mature forest with several decades of litter accumulation develops a strongly surface-concentrated ^{137}Cs signal while short-lived ^{134}Cs becomes rare (Dolgushin & Korobova, 2021; Ramzaev et al., 2023). Experimental studies from Fukushima and the Chornobyl Exclusion Zone further show that wildfire can enhance retention of particulate ^{137}Cs in surface soils rather than promote rapid leaching to deeper horizons (Igarashi et al., 2024; 2026). Our observations are consistent with this interpretation, as the post-fire radiocaesium signal remained concentrated within the shallow ash–charcoal layer and did not indicate substantial downward mobilization. Similar conclusions have been reported from Ukrainian post-fire forest studies, where radionuclide activities remained below regulatory concern despite burning

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(Popovych et al., 2022).

4.9. Implications for Long-term Environmental Monitoring

The radionuclide dataset provides a practical baseline for long-term monitoring of the Amankaragai massif and other island pine forests of the Turgai depression. Because all measured activities remained below MPC values, the present soils can serve as a reference background against which any future accidental or chronic deposition can be evaluated (Holiaka et al., 2020; Dolgushin & Korobova, 2021). The combined depth dependence of ^{137}Cs and its positive relationship with ^{40}K support the use of a normalized $^{137}Cs/^{40}K$ activity ratio as a diagnostic indicator for future monitoring, following approaches applied in long-term European radiological programmes (Stoulos & Loannidou, 2025). Re-sampling of the existing 36-point grid at five-year intervals, together with additional sampling after future prescribed burns or wildfires, would provide a robust framework for detecting changes in radiological status. Overall, the evidence indicates that wildfires in these currently uncontaminated island pine forests do not constitute a significant radiological hazard. The post-fire soil profile retained the typical surface-concentrated ^{137}Cs signature, while both mobile and total forms of potentially toxic elements remained below MPC/APC values (Dolgushin et al., 2020; Holiaka et al., 2020; Ramzaev et al., 2023). Continued observation of the few plots in which ^{134}Cs was detected would nevertheless provide a useful opportunity to verify the long-term decay and redistribution dynamics of this remaining Chernobyl-derived tracer under the dry-steppe conditions of Northern Kazakhstan.

4.10. Limitations of Two-year Monitoring

This study should be interpreted in light of several constraints inherent in its two-year (2023–2024) post-fire design following the September 2022 Amankaragai burns. The observation window captures only the earliest stage of pyrogenic succession and cannot resolve longer-term trajectories — for example, whether the near-dominance of *Calamagrostis epigeios* will persist or wane over decades, whether natural regeneration of *Pinus sylvestris* will eventually succeed through the suppression of this competitive rhizomatous grass layer, or whether the A0/A1 horizon will reconstitute on the centennial timescales reported for sandy post-fire substrates elsewhere. Because the campaign examines a single fire event at a single point in time, with no chronosequence of differently-aged burns, statements about recovery rates rest on international chronosequence analogues rather than on on-site temporal replication. The sampling design is confined to the A0, A1 and upper mineral layers (2nd and 3rd genetic horizons) within the 36-point grid, so deeper mineral-profile dynamics and broader spatial generalisability remain unconstrained. Activities of ^{226}Ra, ^{232}Th and ^{134}Cs were detected in only a few samples, and the two-year window cannot yet resolve the longer-term vertical migration kinetics of radiocaesium in these sandy substrates. Equally, the two geobotanical snapshots do not yet permit separation of inter-annual weather variability from the true post-fire recovery trajectory, particularly under the sharply continental, semi-arid climate of the Turgai depression, where ~310 mm of annual precipitation imposes a strong hydrological constraint on vegetation. Finally, the proposed 5-year and 3–5-year restoration timeframes and the recommended five-yearly re-inventory cycle explicitly acknowledge that the present dataset cannot validate them, and are framed as future monitoring actions whose efficacy must be tested by repeated observation; together, these limitations define the current applicability of the findings and underscore the need for sustained, long-term post-fire monitoring at the Amankaragai site.

5. CONCLUSION

This study provides the first plot-based, multi-indicator assessment of post-fire pyrogenic succession and upper-horizon soil quality in the Amankaragai island pine forest of Northern Kazakhstan. Where previous investigations in the country have addressed only a single component — remote-sensing regeneration, short-term heavy-metal redistribution, or the conservation status of individual pine massifs — the present design links, within the same control/burned/cleared comparison, vegetation activity, pyrophyte survival, meadow-steppe formation, A0/A1-horizon morphology, agrochemical status, total forms of potentially toxic elements, and γ-radionuclide activity. This combination creates the quantitative baseline against which both future fires and active restoration actions in the Amankaragai forest can now be evaluated. Three practical implications follow directly from the findings. First, leaving burned stands intact is preferable to post-fire salvage logging, because clearing the burned site converted the pine community into a steppe community and raised the synanthropization coefficient to 29.7%, in agreement with field evidence that, sixteen years after a fire-plus-salvage combination in dry *Pinus sylvestris* forests elsewhere, natural pine regeneration remains insufficient. Second, the dominant barrier to natural *Pinus sylvestris* recovery in the short term is a single species — *Calamagrostis epigeios* — whose dense rhizome system suppresses seedlings, a finding consistent with European evidence that this species "stops the course of succession", and with boreal recommendations to create competition-free seedbeds in *Calamagrostis*-dominated post-fire sites.

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Third, all soil-quality and radiological indicators remained below their respective maximum permissible concentrations in every sample, including the strongly affected upper horizons, so the Amankaragai soils can serve as a stable in-situ reference ("pedological memory") for future monitoring programmes. Five mutually reinforcing restoration actions are recommended for the massif: prohibition of post-fire salvage logging in first-category fire-hazard stands for 3–5 years after fire; targeted suppression of *C. epigeios* combined with competition-free mineral-soil scalps of ≥ 1 m² before natural seedfall; active rebuilding of the A0/A1 horizon by mulching with needle litter collected from adjacent unburned stands; re-planting of *Pinus sylvestris* on mineral scalps in years 2–3 after fire combined with shelter-underplanting using *Picea obovata* and *Betula pendula* following dry-pine protocols elsewhere; and repeat inventory of the same plot grid at five-year intervals, with the $^{137}Cs/^{40}K$ ratio adopted as a diagnostic index against any future deposition event. Together these actions constitute an arid-steppe-specific operationalisation of the global post-fire restoration frameworks now available and place the Amankaragai forest in the dual role of a pilot restoration site and a permanent monitoring reference for the relic island pine stands of the Turgai depression. Against a backdrop of accelerating climate-driven fire activity, restoration of these forests should be treated as a strategic national priority.

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Data Availability: All the data is available in the article.

Ethics Statement: This study involved field observations of vegetation and laboratory analyses of soil samples and did not involve human participants or experimental animals. Therefore, ethical approval was not applicable.

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Attachments: Appendix 1-4

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