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Research Article

Assessment of the Dynamics and Condition of Post-Fire Forest Recovery in the Amankaragay Massif, Kostanay Region, Republic of Kazakhstan

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Abstract
The study evaluates the dynamics and condition of post-fire forest recovery in the Amankaragay massif of the Kostanay region, Republic of Kazakhstan, which has been subjected to both natural and anthropogenic pyrogenic influences, resulting in structural transformations within the forest ecosystems and pyrogenic succession processes. The objective of this research is to assess natural forest regeneration after wildfires through an integrated approach, combining field studies and remote sensing data, and to analyze structural changes in forest landscapes due to fire disturbances. Three sample plots were selected for analysis: all affected by wildfires between 2004 and 2024, with assessments carried out using high- and medium-resolution satellite imagery. The methodology included the use of differenced normalized burn ratio (dNBR) analysis to assess fire severity, normalized difference vegetation index (NDVI) analysis to evaluate the intensity and dynamics of post-fire vegetation recovery, and geospatial analysis using ArcGIS 10.8. Additionally, supervised classification of satellite imagery and field surveys were conducted to validate remote sensing data. The results indicate significant structural changes in forest-forming species following fire disturbances, confirmed by both remote sensing and field data. As a result, the natural regeneration of forest ecosystems was evaluated, and significant findings were obtained. Fire intensity and type influence the rate of forest recovery. The dNBR and NDVI analyses confirm the effectiveness of remote sensing for monitoring post-fire forest recovery. Remote sensing data and field assessments enable not only the evaluation of the current forest condition but also predictions for its future development. This study underscores the effectiveness of remote sensing techniques in evaluating pyrogenic succession and contributes to a deeper understanding of natural forest regeneration processes in the region. The findings can inform the development of evidence-based strategies for forest ecosystem management and post-fire restoration efforts.

Keywords: forest, dynamics, post-fire forest recovery, pyrogenic succession, remote sensing of the earth, Kostanay region

1. INTRODUCTION

Wildfires are an inherent component of natural ecosystem dynamics, exerting a profound influence on forest structure and functioning. They drive transformations in vegetation cover, alter soil conditions, initiate successional processes, and may lead to biodiversity loss. The interaction of pyrogenic factors with climatic and anthropogenic influences positions wildfires as a major driver of ecosystem changes, affecting their productivity and resilience [1]-[3]. In recent decades, the frequency and intensity of wildfires have significantly increased due to a combination of natural and anthropogenic factors. Key contributing factors include intensified land use, population growth, increased recreational pressure on forested areas, and global climate change, which exacerbates temperature rise and prolongs drought periods [4]. Climate change projections indicate an escalating risk of extreme wildfire events soon, underscoring the urgent need for scientifically grounded approaches to the restoration of disturbed forest ecosystems [5][6].

Contemporary research on post-fire forest regeneration focuses on elucidating the mechanisms of natural vegetation recovery, identifying the factors influencing its dynamics, and developing effective forest restoration strategies. In this context, remote sensing methods play a crucial role in spatiotemporal monitoring of post-fire landscapes. Spectral indices such as the normalized burn ratio (NBR) and the normalized difference vegetation index (NDVI) are among the most effective tools for quantitatively assessing fire-induced forest damage, analyzing regeneration dynamics, and forecasting subsequent successional trajectories. The integration of satellite data with field research findings enables the acquisition of objective, high-resolution information on forest ecosystem recovery, positioning this approach as

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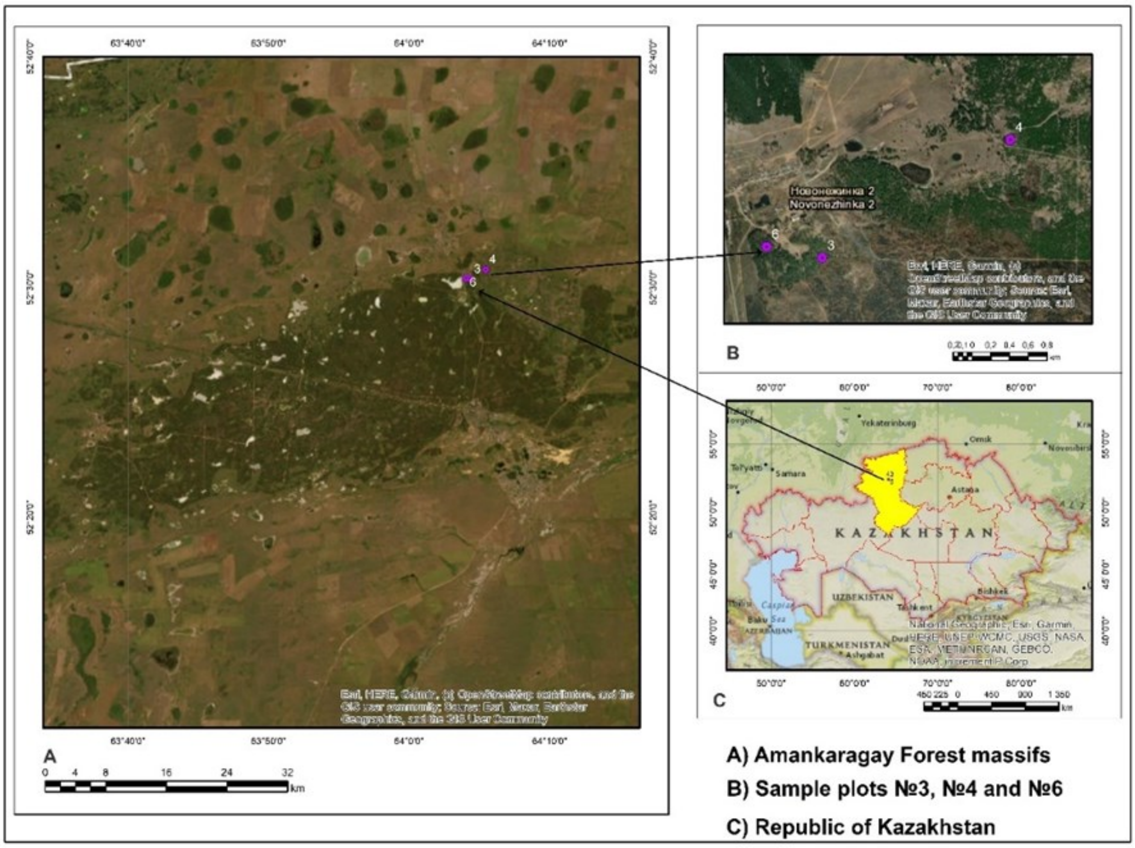


Figure 1. Maps of Amankaragay forest massif, Kostanay region.

one of the most advanced methodologies for assessing wildfire impacts.

A substantial body of scientific literature has been dedicated to the study of post-fire forest dynamics and vegetation recovery analysis, employing both field-based and remote sensing methodologies [7]-[14]. These studies emphasize the critical role of spectral indices and contemporary technologies in monitoring and predicting forest recovery processes. The utilization of NDVI, NBR, and other spectral indices facilitates the assessment of forest degradation severity, regeneration potential, and spatial recovery patterns. Nonetheless, conducting large-scale field studies in forest ecosystems is associated with considerable logistical and financial challenges. Consequently, an integrated approach that combines remote sensing techniques with field observations represents the most reliable and cost-effective method for evaluating post-fire forest recovery. The recent large-scale wildfires in the Amankaragay massif of the Kostanay region, Kazakhstan, have resulted in substantial alterations to vegetation cover, disruptions in soil-hydrological conditions, and modifications of microclimatic parameters. The assessment of post-fire forest regeneration in this massif is of paramount importance for understanding recovery processes and developing effective strategies for the restoration of disturbed ecosystems.

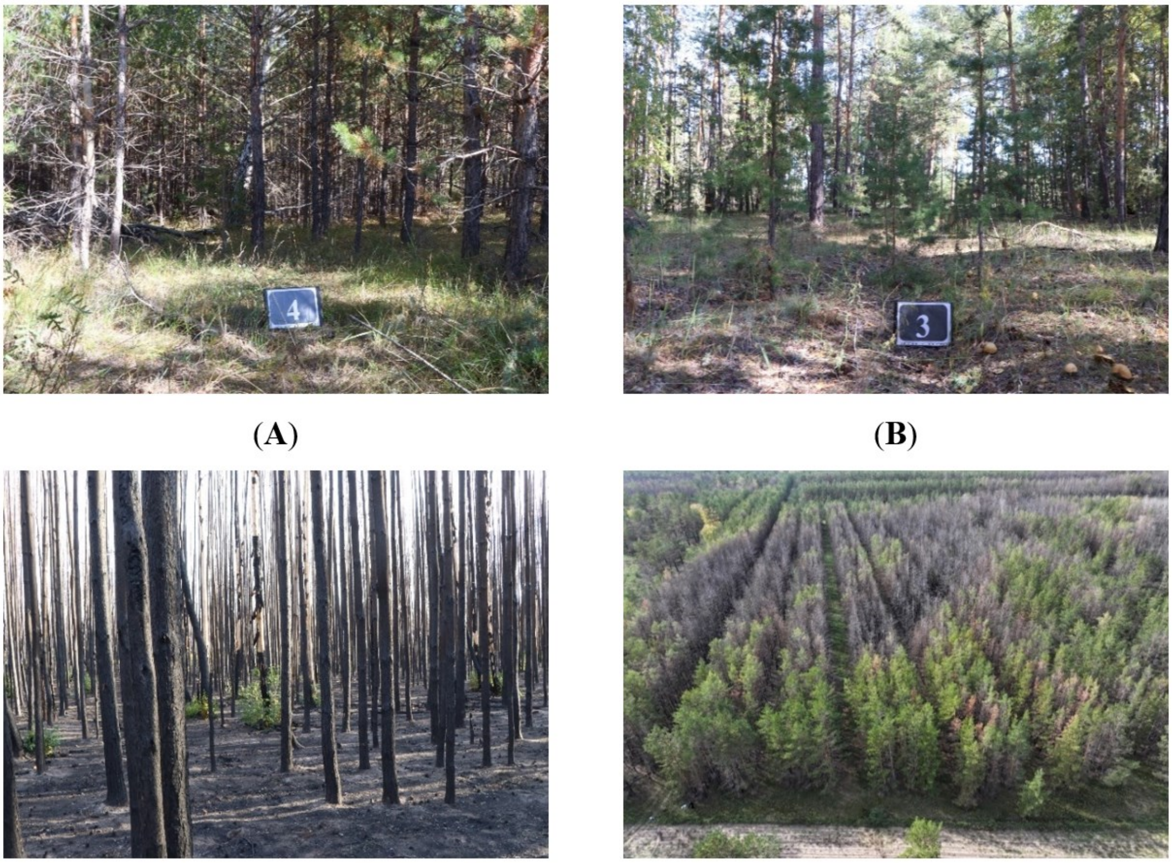
This study is dedicated to evaluating the dynamics and current state of natural forest regeneration in the Amankaragay massif. The novelty of this research lies in its comprehensive approach to post-fire forest ecosystem assessment, integrating field observations, remote sensing methodologies, and GIS-based analysis. For the first time, a detailed examination of the natural regeneration dynamics of the Amankaragay massif following a wildfire is conducted using cutting-edge technologies, providing a high-resolution depiction of recovery processes. The findings of this study hold significant implications for the development of scientifically substantiated forest management, conservation, and restoration strategies under changing climatic conditions, as well as for advancing methodologies for assessing the ecological consequences of wildfires.

2. MATERIALS AND METHODS

2.1. Study Area and Research Object

The subject of this study is the forests of the Amankaragay Massif, located in the Kostanay Region in the northern part of the Republic of Kazakhstan. This region is characterized by a diverse landscape and a combination of different natural zones, where steppe ecosystems coexist with extensive coniferous and deciduous forests. The Amankaragay Forest extends along the southern part of the Kostanay (North Turgay) Plain, with a length of 45 km and a width of 14.5 km. The total area of the forest massif exceeds 60,000 ha. The eastern and western sections of the Amankaragay Massif are relatively well-preserved and are characterized by hilly terrain interspersed with a system of small saline lakes, ranging in depth from 5 to 7 m. This landscape represents a unique ecosystem where forest, steppe, and aquatic biotopes interact, contributing to the biodiversity and ecological balance of the region [15].

The pine forests of the Amankaragay Massif are characterized by high fire susceptibility and a frequent occurrence of wildfires, which is primarily due to the arid conditions in which they grow. The increasing number and frequency of pyrogenic disturbances in natural systems over recent decades can be attributed to both climatic and anthropogenic factors. According to the forest fire zoning classification, the study area belongs to the Amankaragay Wildfire District, where the fire-prone period lasts 208 d. Between 2001 and 2024, a total of 88 wildfires were recorded within the forest management area, affecting a total of 5,249.9 ha, of which 5,010.7 ha were forest stands and plantations [16]. This study aims to analyze the processes of natural forest regeneration following a wildfire in the Amankaragay Forest Massif (Figure 1). A comparative analysis of three sample plots is



(A) **(B)** **(C)** **(D)**

Figure 2. Natural forest regeneration, (a) natural regeneration of pine at the 4th sample plot, (b) natural regeneration of pine at the 3rd sample plot, (c) key area: Birch regrowth after the 2022 fire, and (d) aerial view of the 4th sample plot.

Figure 3. Natural regeneration of pine at the 6th sample plot.

conducted using remote sensing data and field observations.

Sample plot No. 4 (52°30′47.54′" N, 64° 5′26.08′′ E) is located within the Novonezhinsky Forestry of the Semiozernoye Forest Management Unit. This site was affected by a moderate-intensity crown fire in 2004, and in 2014, a localized surface fire was recorded along its periphery (Figure 2). To evaluate the forest's natural regeneration potential, a site previously impacted by a large-scale fire was selected as the sample plot. At the time of the survey, both naturally regenerated stands and artificially established forest plantations were observed within the area.

Sample plot No. 3 (52°30′24.12′′ N, 64°4′0.61′′ E) is located within the Novonezhinsky Forestry of the Semiozernoye Forest Management Unit (Figure 2). The site is predominantly composed of naturally regenerated tree stands, with occasional occurrences of silver birch (Betula pendula) within the forest canopy. In 2004, the area was affected by a moderate-intensity surface fire, while in 2014 and 2022, low-intensity surface fires impacted its periphery.

Sample plot No. 6 (52°27′19.50′′ N, 64° 26′17.24′′ E) experienced a low-intensity surface fire in 2004, followed by localized surface fires along its periphery in 2014 and 2022. It is situated in Compartment 32, Quarter 7 of the Novonezhinsky Forestry within the Semiozernoye Forest Management Unit (Figure 3).

The Amankaragay forest massif represents a unique natural landscape with high ecosystem diversity. Its investigation in the context of post-fire forest recovery is crucial for understanding vegetation dynamics under changing climatic conditions and increasing anthropogenic pressures. The selection of sample plots was based on the following criteria: areas affected by fires of varying intensity and severity; long-unburned sites to assess natural forest regeneration processes; and the availability of a sufficient number of high-resolution archival satellite images with minimal cloud cover, spanning the longest possible period (up to 20 years), enabling precise determination of fire occurrence dates.

2.2. Methods

For the analysis of forest recovery dynamics in the post-fire period, both field research methods and remote sensing techniques were employed. The study included the processing and analysis of field observation data, as well as high-resolution satellite imagery from Landsat 8, Landsat 7, and Sentinel-2. Additionally, data from the Goddard Space Flight Center of NASA (https://modis-land.gsfc.nasa.gov/fire.html) and the orman.gharysh.kz portal (National Company "Kazakhstan Gharysh Sapary") were also utilized. To assess the dynamics of forest recovery in the Kostanay region during the post-fire period, the temporal range from 2005 to 2024 was selected. The analysis employed spectral indices (dNBR, NBR, NDVI) to evaluate the extent of vegetation damage and the dynamics of its recovery. The dNBR was selected for assessing the extent of vegetation damage due to its proven ability to effectively detect fire-induced changes and provide a quantitative measure of the severity of disturbances. The NBR is employed for precise differentiation between burned and unburned areas, especially within forest ecosystems, enabling the accurate delineation of fire-affected zones [17][18].

The NDVI was used to monitor the recovery of vegetation, highlighting changes in vegetation density and health over time. Remote sensing data were supplemented with field study results. Field studies involved identifying the composition of tree species and their relative proportions, evaluating seedling health, measuring seedling height and diameter, and determining seedling density per ha [19]-[21]. Furthermore, supervised classification of satellite imagery was utilized in the study. This method enabled the classification of various land cover types, including regenerating forest areas, based on training datasets and predefined classes. The application of supervised classification allowed for the differentiation of forest areas into specific types, such as pine, birch, and deciduous forests, and facilitated the identification of post-fire recovery zones. This methodological approach enhanced the precision of the analysis and allowed for more granular detection of landscape changes, which are not always discernible through spectral indices alone [22].

The data obtained were processed using GIS analysis techniques and image classification methods, incorporating both automated and visual interpretation approaches. The algorithm developed for analyzing the dynamics of forest ecosystem recovery facilitated the identification of key sample plots and the assessment of regeneration trends under natural recovery conditions. This algorithm accounts for changes in vegetation structure and enables the identification of areas that have experienced significant transformation due to fire disturbances, as well as those exhibiting successful recovery. The algorithm for analyzing the dynamics and status of post-fire forest recovery in the Amankaragay massif of the Kostanay region, following pyrogenic impacts, is presented in Figure 4. This approach provided a comprehensive evaluation of the recovery processes, identifying areas with varying levels of regeneration and allowing for the prediction of future ecosystem trajectories based on the intensity of disturbances and environmental conditions.

To analyze the dynamics of burned areas and quantify fire disturbance levels, the NBR and dNBR were employed [17][18]. Among the various spectral indices used to assess wildfire-affected areas, the NBR remains one of the most widely applied [23]. The primary criterion for burn scar identification is the reduction in spectral reflectance in the near-infrared (NIR) region. The NBR is calculated using the following equation 1;

$$NBR = (B_{NIR} - B_{SWIR}) / (B_{NIR} + B_{SWIR}) \quad \textbf{(1)}$$

where BNIR and BSWIR correspond to the spectral bands of multispectral satellite imagery within the wavelength ranges of 0.75–0.90 µm and 2.09–2.35 µm, respectively. This index is based on

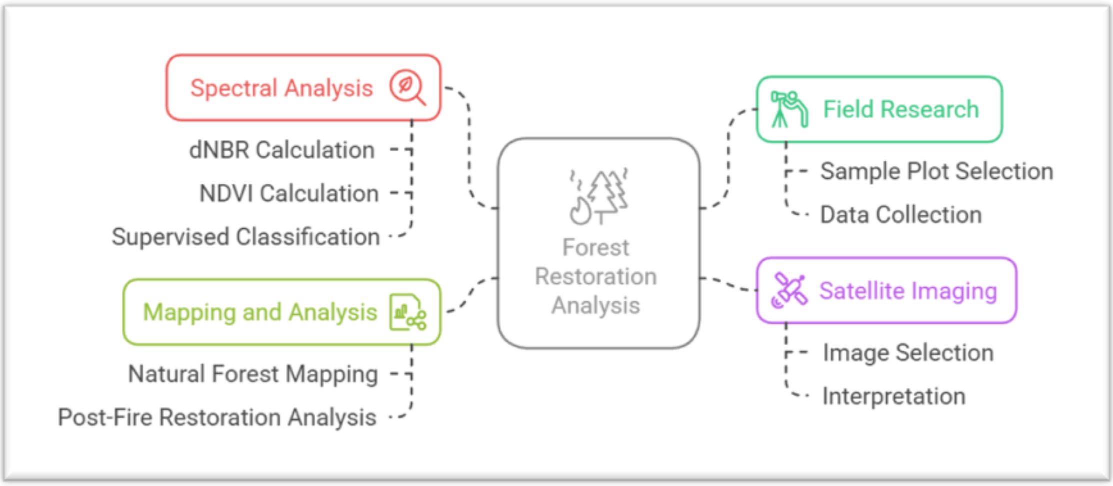


Figure 4. Algorithm for analyzing the dynamics and condition of post-fire forest recovery in the Amankaragay Massif, Kostanay Region, Republic of Kazakhstan.

Table 1. Classification of dNBR values.

dNBR Value	Burn Severity Classification
Above 0.66	High post-fire disturbance
0.66–0.27	Moderate post-fire disturbance
0.27–0.10	Low post-fire disturbance
Below 0.10	Minimal or no fire impact

the relationship between NIR and shortwave infrared (SWIR) reflectance. To quantitatively assess fire impact within the study area, the dNBR was utilized. This index represents the difference between pre-fire and post-fire NBR values derived from Landsat 7, Landsat 8, and Sentinel-2 satellite imagery. The dNBR, which refines the NBR, is calculated as follows Eq. 2. where NBR_prefire denotes the NBR value obtained prior to the wildfire, while NBR_postfire represents the NBR value measured following the wildfire.

$$dNBR = NBRprefire - NBRpostfire \quad (2)$$

According to this equation, areas with pixel values close to or equal to 0 indicate unburned regions, while values approaching 1 correspond to severely burned areas. The dNBR spectral index exhibits high sensitivity to fluctuations in leaf moisture content and chlorophyll levels. The classification of burn severity based on dNBR values is presented in Table 1 [18].

The condition of forest vegetation in fire-affected areas is effectively evaluated using the NDVI [20], which serves as a relative indicator of photosynthetically active biomass [8][19][21]. NDVI values range from -1 to 1 and are directly related to the total vegetation biomass. This index, along with other spectral indicators, is widely utilized to assess changes in both the quantitative and qualitative structure of forest ecosystems [10][24]-[29]. When combined with field-based assessments, these indices provide accurate and comprehensive analytical results. The NDVI is computed using the following Equation 3, where NIR and RED represent the spectral bands of multispectral satellite imagery obtained from Landsat 7, Landsat 8, and Sentinel-2.

$$NDVI=(NIR-RED)/(NIR+RED) \quad (3)$$

NBR and NDVI values exhibit a strong correlation with field evaluations of fire-affected areas. These indices are extensively utilized by the U.S. Forest Service to assess wildfire-induced forest damage [30], identify recent burn scars, and determine fire severity across various vegetation zones. An NDVI value ranging from 0.00 to 0.20 indicates the absence of vegetation, suggesting barren land or areas with minimal plant cover. A range of 0.20 to 0.31 corresponds to sparse biomass growth, representing regions with low-density vegetation. NDVI values between 0.30 and 0.60 signify moderate biomass accumulation, indicating well-established but not fully dense vegetation. Finally, an NDVI range of 0.60 to 1.00 reflects dense biomass development, characteristic of healthy and well-developed plant communities [19][21].

3. RESULTS AND DISCUSSIONS

The constructed maps based on the dNBR burn index reflect the dynamics and characteristics of vegetation cover restoration in burned areas, similar to the indicators of the NDVI vegetation index. Many researchers note a high correlation between the NBR and NDVI indices and ground data. Based on the calculation of the NBR and dNBR indices from 2003 to 2024, we analyzed the level of disturbance in forest areas 3, 4, and 6 of the Amankaragay forest massif during the period from 2003 to 2025 (Figure 5).

Based on the research results, in 2005, the clear-cut areas in sample plot No. 4 covered 40,060 m² (94.5% of the studied area), occupying a significant portion of the plot, whereas in sample plots No. 3 and 6, the clear-cut areas were only 5.5% and 28.3%, respectively. This indicates significant differences in the extent of anthropogenic impact and forest cover across different periods. Following the 2014 wildfire, the sample plots were partially affected by fires with low to moderately low damage levels: sample plots No. 3 and 6 showed minor disturbances, while in sample plot No. 4, the damage level was moderate (13.8% of the total area), which likely slowed the natural forest regeneration process. A major wildfire in 2022 in the Amankaragay forest massif further impacted the forest areas of sample plots No. 3 and 6, both of which experienced low damage levels: sample plot No. 3 was affected over 18.8% of its area (11,880 m²), while sample plot No. 6 was affected over 20.1% (19,130 m²). Despite the repeated fires, the plots show the capacity for natural regeneration; however, the rate of vegetation recovery varies depending on the intensity and frequency of disturbances, as well as landscape conditions.

The results of pyrogenic disturbances in these forest areas were validated by field studies conducted on key sample plots in 2022–2024. Verification of remote sensing data (RS) demonstrated a high correlation between field measurements and the values of the dNBR and NDVI indices. The comparative analysis enabled the evaluation of vegetation recovery and confirmed the accuracy of the classification based on satellite monitoring data. Field studies on the sample plots included a comprehensive assessment of forest ecosystem recovery after fire. The composition and structure of tree communities, indicators of natural regeneration, and the spatial distribution of key tree species were analyzed. Special attention was given to the dynamics of recovery in light coniferous and deciduous forests, their proportional distribution, and the influence of landscape conditions. The data obtained allow for the characterization of the current stage of forest regeneration and identification of the key factors that determine its dynamics.

A temporary sample plot No. 4 was established in the study area to assess the natural regeneration of forests in the zone affected by the 2004 moderate -intensity crown fire. In terms of growth, development, and other stand inventory characteristics, the naturally regenerated forest in sample plot No. 4 corresponds to its age, demonstrating good annual growth, with no observed pest or disease damage. The includes older birch stands, while aspen stands are of the same age as the main tree species or younger. These accompanying species are significantly suppressed and are gradually being displaced due to growth cessation. There is also intraspecific natural mortality, with isolated dead and suppressed Scots pine trees, which is typical for high-density stands.

The composition and characteristics of tree species in the burned area of sample plot No. 4 vary in terms of height and percentage distribution. Scots pine (*Pinus sylvestris*) remains the dominant species, covering 50–70% of the area and reaching heights of 5–8 m. Its predominance is attributed to its high fire resistance and ability to regenerate naturally through seed dispersal. Silver birch (*Betula pendula,* 20–30%) and aspen (*Populus tremula*, 5–10%) are pioneer species that facilitate forest recovery, reaching heights of 8–15 m. Willow (*Salix spp.*) is present in moist areas, with a height range of 3–5 m and a total composition not

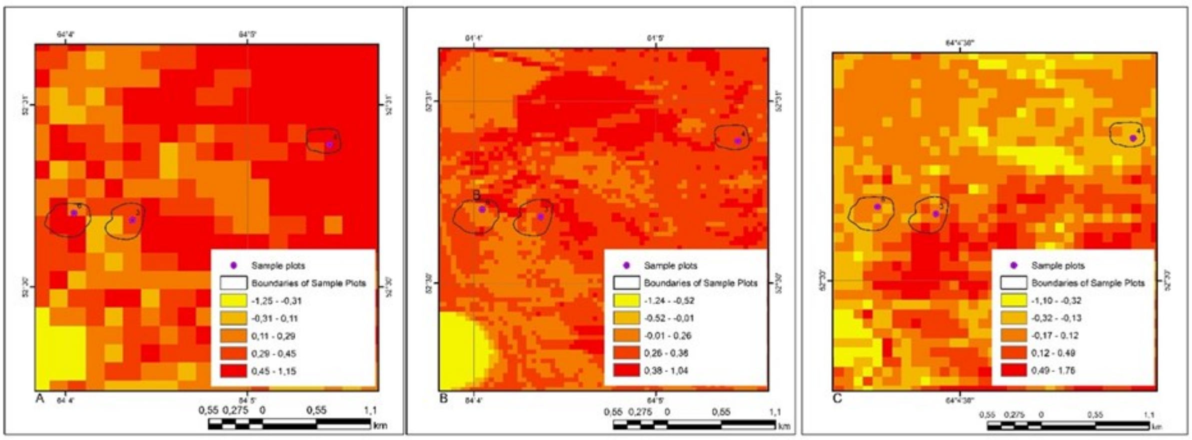


Figure 5. Values of the dNBR index in sample plots 3, 4, and 6 of the Amankaragay forest massif: (A) 2005, (B) 2015, and (C) 2024.

Table 2. Development stages, age, height, diameter, and density of tree stands on sample plot No 4.

Development stage	Age (years)	Height (m)	Diameter (cm)	Density (thousand trees/ha)
Seedlings	1–2	0.1–0.3	<1	1–2
Saplings	3–5	0.3–0.8	<1	3–5
Young stand	6–10	0.8–3	1–5	2–3
Understory	11–20	3–8	5–15	1.5–2

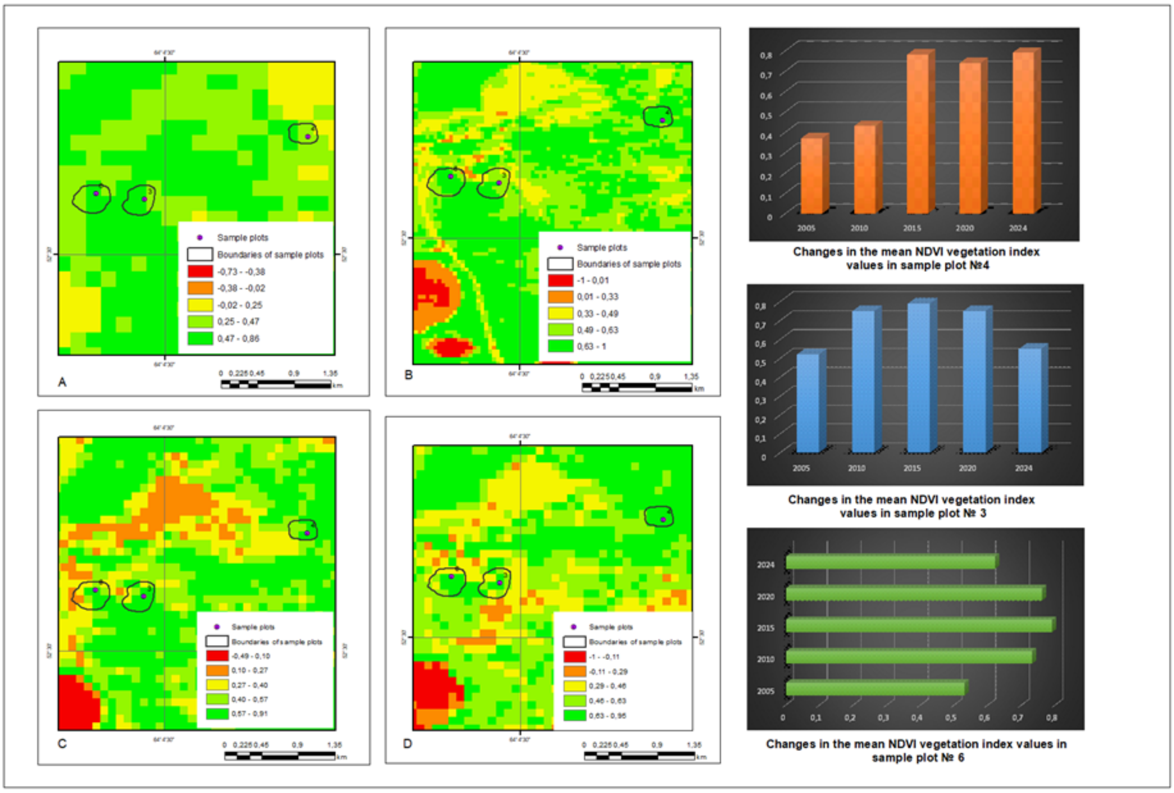


Figure 6. Changes in the NDVI vegetation index from 2005 to 2024.

exceeding 5%. The 2024 data indicate active forest recovery, characterized by a substantial expansion of both coniferous and deciduous forests and a sharp decline in wastelands. This trend is corroborated by observations from sample plots, which record the natural regeneration of Scots pine at various developmental stages (Table 2), confirming the ongoing restoration of the forest ecosystem.

The natural regeneration density of Scots pine on the site ranges from 2,000 to 5,000 seedlings per ha, whereas for silver birch, it ranges from 1,500 to 4,000 seedlings per ha. These values are influenced by local conditions: regeneration is lower in dry areas with high competition from herbaceous vegetation and higher in regions where the ash layer is less compacted and decomposes more rapidly. The recovery of tree vegetation in burn areas is driven by increased light availability, improved nutrient influx, and reduced competition for resources. Sample plot No. 4, which was affected by a moderate-intensity crown fire in 2004, created favorable conditions for natural forest regeneration. Field studies confirm the presence of viable regeneration of tree species, indicating continuous recovery of the forest ecosystem after the fire. To investigate the relationship between field data collected from sample plot No. 4 and the NDVI (Figure 6) and dNBR indices from 2005 to 2024, Pearson correlation analysis was conducted. Sample plot No. 4, which was affected by a moderate-intensity fire in 2004, was selected for analysis as it provided a valuable opportunity to monitor vegetation recovery over the long term (Table 3).

In the early years following the fire (2005–2010), higher dNBR values correlated with lower

NDVI values, indicating slow vegetation recovery. In 2005, the NDVI was 0.37, reflecting significant vegetation damage. Meanwhile, dNBR values remained high, confirming the extent of the fire's impact. By 2015, NDVI had increased to 0.78, showing a notable recovery in vegetation, particularly for species such as silver birch and aspen. During the same period, dNBR decreased, indicating a reduction in vegetation damage. The analysis also revealed a strong positive correlation between NDVI and the density of natural regeneration for Scots pine. In 2015 and 2024, when NDVI values rose to 0.78 and 0.79, respectively, the regeneration density of Scots pine ranged from 3,000 to 10,000 seedlings per ha. Additionally, species such as silver birch and aspen, which are fast-growing pioneers, significantly contributed to the increased NDVI values.

The Pearson correlation coefficient between NDVI and tree density for scot pine and silver birch was 0.86 in 2015, indicating a strong positive correlation. Conversely, the correlation coefficient between dNBR and regeneration density was negative (-0.72 in 2005), suggesting that as fire damage increased (indicated by higher dNBR values), the density of natural regeneration decreased, particularly in areas that suffered more significant damage. These results confirm that the NDVI and dNBR indices are reliable indicators of vegetation recovery dynamics in post-fire zones. The positive correlation between NDVI and regeneration density, along with the negative correlation between dNBR and recovery, shows that moderate fire damage (low dNBR values) supports successful regeneration, particularly of species such as Scots pine, birch, and aspen, while more severe damage (high dNBR values) hinders recovery.

Field verification of the data confirms the recovery of Scots pine, which remains the dominant species, covering 50–70% of the area. The formation of the understory and moss layer indicates the gradual restoration of the ecosystem. The prevalence of Scots pine suggests the establishment of a stable coniferous-deciduous forest, while the notable presence of silver birch and aspen reflects an early successional stage. The sample plot No. 3 is located in an area predominantly covered by naturally regenerated forest stands, with isolated individuals of pendulous birch interspersed within the canopy. In 2004, the area was subjected to a low-intensity surface fire, with subsequent low-intensity surface fires impacting its peripheral zones in 2014 and 2022. The dominant species in sample plot No. 3 is Scots pine, comprising 70–85% of the tree canopy, with individuals reaching heights of 8–12 m and diameters of 15–25 cm. Pendulous birch accounts for 10–15% of the stand, and aspen makes up 5–10%, with both species reaching heights of 6–12 m and diameters of 10–20 cm. Willow is present in small quantities (< 5%), predominantly in moist areas. Scots pine remains the dominant species (70–

Table 3. Post-fire NDVI and dNBR Index Trends on Sample Plot No. 4 (2005–2024).

Years	NDVI Index	dNBR Index
2005	0.37	1.25–0.31
2010	0.43	0.31–0.11
2015	0.78	0.11–0.29
2020	0.74	0.29–0.45
2024	0.79	0.45–1.15

Table 4. Development stages, age, height, diameter, and density of tree stands on sample plot No. 3.

Development stage	Age (years)	Height (m)	Diameter (cm)	Density (thousand trees/ha)
Seedlings	1–2	0.1–0.3	<1	2–5
Saplings	3–5	0.4–0.8	<1	3–6
Young stand	6–10	1–4	2–7	2–4
Understory	11–20	4–10	6–18	1.5–3

Figure 7. Natural regeneration of pine.

85%) in the stand, contributing to the resilience of the coniferous forest's regeneration. Pendulous birch and aspen assume a secondary role in the early stages of ecological succession, gradually being replaced by Scots pine. Willow is found infrequently (<5%). Natural regeneration is proceeding at a relatively high rate, facilitated by seed regeneration processes and the retention of mother trees, which significantly contribute to the successional dynamics (Table 4).

Young forest stands in sample plot No. 3 are subject to a range of biotic and abiotic factors, including the presence of insect pests (*Dendrolimus pini*, bark beetles), herbivorous mammals (e.g., roe deer, wild boar, and rodents), and climatic stressors such as drought, all of which influence their growth and development. The density of natural regeneration of Scots pine fluctuates between 3,000 and 7,000 seedlings per ha, while silver birch exhibits a regeneration density between 2,000 and 5,000 seedlings per hectare, with variation dependent on the specific microenvironmental conditions of the site. The presence of mature, seed-bearing trees plays a crucial role in the process of natural regeneration by ensuring a continuous supply of viable seeds. At the periphery of sample plot №3, the natural regeneration of Scots pine has been facilitated by an abundance of rainfall recorded between August 30 and September 20, 2023. The formation of seedlings, aged 20–30 days, is closely associated with the proximity of intact seed trees, which ensure a sustained influx of diaspores. The average regeneration density is approximately 1–2 seedlings per m^2. However, localized concentrations of seed material were observed in depressional relief features with heightened hydromorphy and in areas with disturbed soil structure, suggesting favorable conditions for autogenic succession and the recovery of the forest community (Figure 7).

At the periphery of sample plot No. 3, isolated instances of suppressed growth in young tree stands have been observed, which could be linked to the presence of *Rhizina undulata*. This fungus, commonly found in areas affected by fire and burned soils, infects the root systems of Scots pine trees aged 20–50 years, leading to conditions that hinder seedling growth. In contrast, deciduous species such as silver birch and aspen exhibit greater resistance to its effects, thereby promoting their successful establishment and growth on the site (Figure 8).

In 2024, a multilayered Scots pine forest with a high density of natural regeneration was established on sample plot No. 3, which had been impacted by a surface fire. Tree heights ranged from 8 to 12 m, with trunk diameters between 10 and 22 cm. The density of Scots pine regeneration varied from 7,000 to 11,000 trees per ha, surpassing the regeneration densities observed in areas affected by crown fires. The recovery process on this plot is proceeding at a faster rate compared to sample plot No. 4, where a crown fire caused more severe alterations to the ecosystem, thereby decelerating the regeneration of the forest stands. To investigate the relationship between field data collected from sample plot No. 3 and the NDVI (Figure 6) and dNBR indices from 2005 to 2024, Pearson correlation analysis was performed. Sample plot No. 3, which was affected by a low-intensity surface fire in 2004, followed by subsequent low-intensity surface fires in 2014 and 2022, was selected for analysis due to its valuable potential for tracking vegetation recovery over an extended period (Table 5). This plot provided an opportunity to observe vegetation recovery after multiple fire events of varying intensity, allowing for the identification of key patterns in the recovery process.

In the initial post-fire years (2005–2010), high dNBR values correlated with low NDVI values, indicating slow vegetation recovery. In 2005, the NDVI value was 0.52, reflecting significant vegetation damage, and high dNBR values confirmed the extent of the fire's impact. By 2010, the NDVI had increased to 0.75, indicating noticeable recovery of vegetation, particularly for species such as silver birch and aspen. During the same period, dNBR values decreased, reflecting a reduction in fire-induced damage. Further analysis revealed a strong positive correlation between NDVI and the density of natural regeneration for Scots pine. In 2015 and 2024, when NDVI values were 0.79 and 0.75, respectively, the regeneration density of Scots pine ranged from 3,000 to 10,000 seedlings per ha. Additionally, species such as Betula pendula and Populus tremula, which are fast-growing pioneer species, contributed significantly to the increase in NDVI values. The Pearson correlation coefficient between NDVI and tree density for Scots pine and silver birch was 0.90 in 2015 and 0.75 in 2024, demonstrating a strong positive correlation. In contrast, the correlation between dNBR and regeneration density was negative (-0.72 in 2005), indicating that as fire-induced damage (reflected in higher dNBR values) increased, the density of natural regeneration decreased, particularly in areas more severely affected by fire.

These findings indicate that sample plot No. 3 showed relatively rapid ecological recovery. Despite the fire in 2022, the site continues to demonstrate natural regeneration, supported by the presence of seed trees of Scots pine, favorable moisture conditions in depressional areas, and active recovery of the herbaceous and shrub layers. These results confirm that the NDVI and dNBR indices are reliable indicators of vegetation recovery dynamics in post-fire ecosystems. The positive correlation between NDVI and regeneration density, coupled with the negative correlation between dNBR and recovery, highlights that moderate fire damage (low dNBR values) promotes successful regeneration, whereas more severe fire damage (high dNBR values) impedes recovery.

Sample plot No. 6 exhibits active forest recovery, with a balanced distribution of coniferous and broadleaf species, reflecting broader regional trends in forest composition. As of 2024, the area of light-coniferous forests is 29,082 hectares, and the area of broadleaf forests is 30,056 hectares, indicating a nearly equal spread of Scots pine and broadleaf species. Within this plot, Scots pine and silver birch dominate the tree composition, resulting in a mixed forest structure. The average height of Scots pine is 6.5 m, with a stem diameter of 12.3 cm, while silver birch reaches 9.2 m in height. Aspen grows up to 12.8 m, and willow remains relatively rare, occupying predominantly wetter

Figure 8. Wavy rhizina mushroom (*Rhizina undulata*).

Table 5. Post-fire NDVI and dNBR Index Trends on Sample Plot No. 3 (2005–2024).

Period	NDVI Index	dNBR Index
2005	0.52	1.10–0.32
2010	0.75	0.32–0.13
2015	0.79	0.17–0.12
2020	0.75	0.12–0.49
2024	0.55	0.49–1.76

Table 6. Development stages, age, height, diameter, and density of tree stands on sample plot No. 3.

Development stage	Age (years)	Height (m)	Diameter (cm)	Density (thousand trees/ha)
Development stage	1–2	0.12 ± 0.03	< 1	1.4 ± 0.3
Seedlings	3–5	0.35 ± 0.10	< 1	3.8 ± 0.6
Saplings	6–10	1.40 ± 0.50	2.8 ± 1.2	2.5 ± 0.4
Young stand	11–20	5.30 ± 1.80	9.6 ± 3.1	1.7 ± 0.3

areas and constituting approximately 3% of the total tree cover. Sample plot 6 was subjected to a low-intensity surface fire in 2004, followed by localized low-intensity surface fires along its periphery in 2014 and 2022. These fires have contributed to the vigorous natural regeneration of both coniferous and broadleaf species, as indicated by the high density of saplings (Table 6). At present, the plot represents a resilient mixed forest, where Scots pine regenerates alongside birch and aspen, mirroring regional trends in vegetation dynamics.

Sample plot No. 6 is characterized by ongoing natural regeneration processes, despite the presence of pests (such as pine moths and bark beetles), wildlife, and climate stressors, including drought. As of 2024, the plot demonstrates a balanced distribution of coniferous and deciduous species, indicating dynamic changes in the forest structure. Scots pine predominates, establishing a stable stand with a density of 7,000–8,000 trees per ha. In contrast, silver birch and aspen are sporadically distributed, with a density ranging from 3,000 to 3,500 trees per ha, reflecting a notable increase in the proportion of deciduous species within the area. For the study of the relationship between field data collected from sample plot No. 6 and the NDVI and dNBR indices over the period 2005–2024, a Pearson correlation analysis was conducted. Sample plot No. 6, which experienced a low-intensity surface fire in 2004, followed by subsequent low-intensity surface fires in 2014 and 2022, was chosen for analysis due to its value in monitoring long-term vegetation recovery dynamics (Table 7).

In the initial post-fire years (2005–2010), high values of dNBR corresponded with low NDVI values, which indicated a prolonged and gradual recovery of vegetation. In 2005, the NDVI index was 0.53, reflecting significant vegetation damage. During this period, dNBR values remained elevated, corroborating the extent of fire-induced damage. By 2010, the NDVI index had increased to 0.73, signaling a substantial recovery of vegetation, particularly the fast-growing species such as silver birch and aspen. At this time, dNBR values decreased, indicating a reduction in the fire's impact. A further analysis revealed a robust positive correlation between NDVI and regeneration density for Scots pine. In 2015 and 2024, when NDVI values were recorded at 0.79 and 0.76, respectively, regeneration density of Scots pine ranged between 3,000 and 10,000 saplings per hectare. In addition, species such as silver birch and aspen, which are known for their rapid growth, contributed significantly to the observed increase in NDVI values. The Pearson correlation coefficient between NDVI and tree density for both Scots pine and silver birch reached 0.90 in 2015, and remained at 0.75 in 2024, signifying a strong and consistent positive relationship. Conversely, the correlation between dNBR and regeneration density was negative, with a coefficient of -0.72 in 2005. This suggests that as fire-induced damage (indicated by higher dNBR values) increased, the regeneration density declined, particularly in areas subjected to more severe fire impacts. Overall, the results suggest that the forest ecosystem on sample plot No. 6 demonstrated a relatively rapid recovery following fire disturbances. Despite the additional fire event in 2022, the area continues to exhibit robust natural regeneration, driven by the presence of seed trees (primarily Scots pine), favorable moisture conditions in lowland areas, and the active recovery of herbaceous and shrub vegetation.

These findings confirm that both NDVI and dNBR indices are reliable indicators for assessing the dynamics of vegetation recovery in post-fire landscapes. The positive correlation between NDVI and regeneration density, coupled with the negative correlation between dNBR and regeneration, indicates that moderate fire damage (reflected in low dNBR values) facilitates vegetation recovery, particularly for species such as Scots pine, silver birch, and aspen. In contrast, severe fire damage (as indicated by high dNBR values) impedes recovery processes. Natural forest vegetation recovery involves complex ecological and phytocenotic processes, related to the formation of forest biogeocoenoses and the interactions between tree species, soil, and the surrounding environment. The recovery of light-coniferous forests after wildfires, both under the forest canopy and on clearcuts, has been a subject of extensive research. The dynamics of forest ecosystem recovery after fire are influenced by a combination of biotic and abiotic factors, including the degree of disturbance and site conditions. To assess the changes more accurately, image classification was conducted, allowing the identification of key recovery zones and the dynamics of vegetation changes across the sample plots.

The classification maps for sample plots 3, 4, and 6 highlight distinct forest-forming formations and clearly delineate major fire-affected zones, corresponding to areas of barren land and fragmented forest cover (Figure 9). All analyzed plots demonstrate positive indicators of post-fire forest recovery. The most significant vegetation regrowth and dynamic recovery processes are evident in sample plot 4, which experienced the highest level of pyrogenic disturbance, as verified by the multispectral imagery.

The classification maps for sample plots 3, 4, and 6 highlight distinct forest-forming formations and clearly delineate major fire-affected zones, corresponding to areas of barren land and fragmented forest cover. All analyzed plots demonstrate positive indicators of post-fire forest recovery. The most significant vegetation regrowth and dynamic recovery processes are evident in sample plot 4, which experienced the highest level of pyrogenic disturbance, as verified by the multispectral imagery. As further illustrated, the activity of identical forest vegetation species varies across undisturbed forest areas, pyrogenically influenced zones, and directly burned sites. In fire-affected zones, seedling growth processes are intensified due to increased light availability, improved access to mineral nutrients, and reduced interspecific competition in open spaces. These conditions are generally more favorable in pyrogenic zones compared to undisturbed areas [31]-[37].

The dynamics of changes in sample plots No. 3, 4, and 6 from 2005 to 2024 reflect the ongoing process of forest ecosystem recovery, driven by natural factors such as wildfires and deforestation. On all three sample plots, a consistent trend in forest composition alterations is observed, indicating the progression of succession and ecological restoration. In sample plot No. 4, in

Table 6. Development stages, age, height, diameter, and density of tree stands on sample plot No. 3.

Period	NDVI Index	dNBR Index
2005	0.53	1.10–0.32
2010	0.73	0.32–0.13
2015	0.79	0.17–0.12
2020	0.76	0.12–0.49
2024	0.62	0.49–1.76

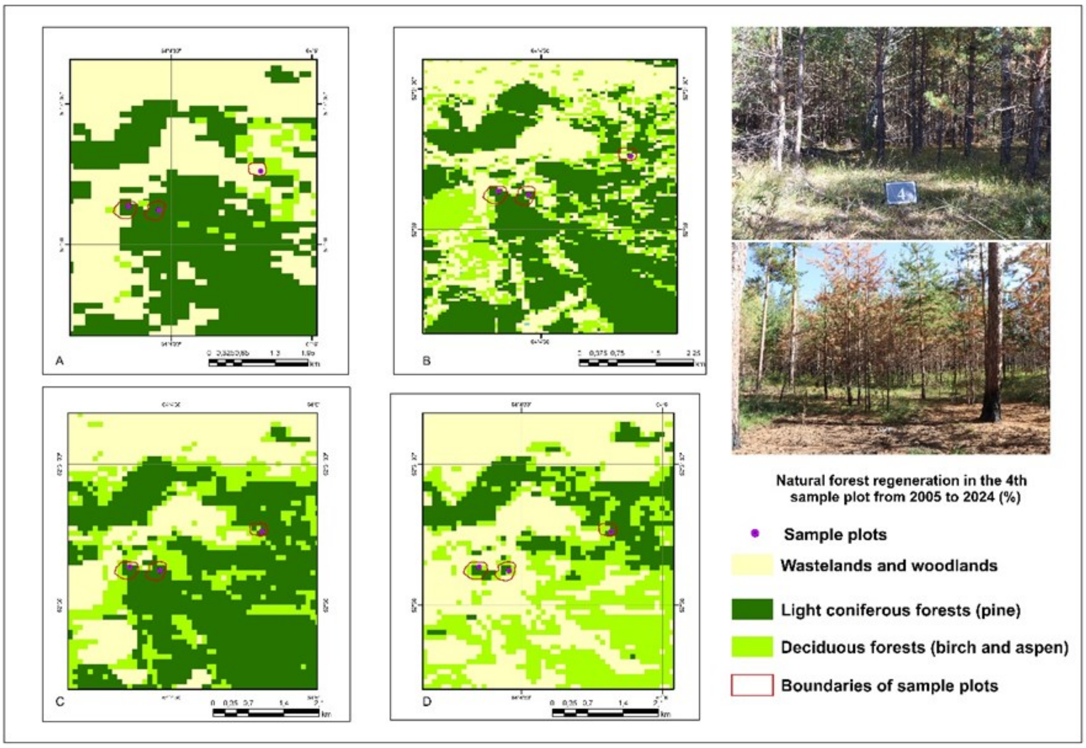


Figure 9. Classification results of Landsat 7 and Sentinel 2 data in (A) July 2005, (B) July 2010, (C) July 2020, and (D) July 2024.

2005, the area of light coniferous forests was 1258 m², the area of deciduous forests was 1068 m², and the area of barren land and sparse forests was 40,062 m². By 2015, the area of light coniferous forests had significantly increased, indicating active recovery of coniferous forests on this plot (Table 8, Figure 10).

The area of deciduous forests also increased significantly, confirming the regeneration of broadleaf species such as birch and aspen. Simultaneously, the reduction in the extent of barren land and sparse forests indicates that these areas are undergoing natural overgrowth. By 2020, the area of light coniferous forests continued to expand, while the extent of deciduous forests had stabilized. Barren land and sparse forests were no longer recorded in the official data, suggesting their transformation into more densely vegetated areas. By 2024, the area of light coniferous forests had slightly decreased, whereas deciduous forests continued to expand. The area of barren land and sparse forests had declined to minimal values, indicating the completion of the barren phase and a transition toward more mature forest ecosystems (Table 9, Figure 11). In 2005, sample plot No. 3 had an area of 61,010 m² covered by light coniferous forests, 1,100 m² by deciduous forests, and 11,100 m² by barren land and sparse forests. By 2015, the area of light coniferous forests had decreased, potentially due to the influence of natural disturbances such as wildfires and anthropogenic impacts like logging.

The increasing of area of deciduous forests confirms the process of coniferous species being gradually replaced by deciduous ones. The significant expansion of barren lands and sparse forests also indicates active vegetation overgrowth. In 2020, the area of light coniferous forests showed an increase, possibly indicating the recovery of coniferous ecosystems, while the area of deciduous forests continued to expand. However, the area of light coniferous forests had markedly decreased, whereas the deciduous forest area had further increased by 2024. The growth in the extent of barren lands and sparse forests may suggest the impact of additional natural factors such as wildfires and climate change.

In sample plot No. 6, in 2005, the area of light coniferous forests was 49,301 m², the area of deciduous forests was 2,500 m², and the area of barren land and sparse forests was 27,275 m². By 2015, the area of light coniferous forests had diminished, a trend attributable to the impacts of natural disturbances (Table 10, Figure 12).

The expansion of deciduous forests indicates a process of substitution, where coniferous species are being replaced by deciduous ones. Concurrently, the reduction in barren lands and rare forest areas suggests ongoing recovery. In 2020, the area occupied by light coniferous forests continued to diminish, while the area of deciduous forests experienced significant expansion. Barren lands and rare forests saw a decline. By 2024, the area of light coniferous forests persisted in its decrease, while deciduous forests continued to increase. The area of barren lands and rare forests expanded, which may indicate the continued progression of forest ecosystem restoration and species replacement.

The overall trend of changes observed across the sample plots suggests a gradual but steady recovery of the forest ecosystems, despite the influences of natural perturbations. Over the study period, all three sample plots exhibited an increase in deciduous forest cover, thus supporting the active regeneration of these ecosystems. Although an initial decline in coniferous forest areas was noted, a subsequent trend of recovery emerged. The area of barren lands and rare forests was significantly reduced over time, corroborating a successful restoration phase and a transition to more mature forest ecosystems. The role of natural factors, such as wildfires and deforestation, as well as successional dynamics, is crucial in explaining these changes, supporting theoretical assumptions regarding the post-disturbance dynamics of forest ecosystems.

In this context, sample plot 4, which experienced the most intense disturbance, demonstrated a protracted recovery process. However, by 2024, high NDVI values were recorded, indicating a considerable degree of vegetation recovery. Sample plot 3 exhibited a faster recovery trajectory, though by 2024, a slight decrease in NDVI values was observed, which could be attributed to structural modifications within the forest. Sample plot 6, which underwent a low-intensity fire, displayed the most stable recovery trajectory, with minimal fluctuations in NDVI values and a gradual reduction in fire-induced damage, as reflected in dNBR changes.

Table 8. Dynamics of forest and vegetation change on sample plot No 4 (m²) from 2005 to 2024.

Period	Light-coniferous forests	Deciduous forest (birch and aspen)	Wastelands and sparse forests
2005	1258	1068	40062
2015	12531	16984	12780
2020	29834	12554	13.2
2024	22500	19823	535

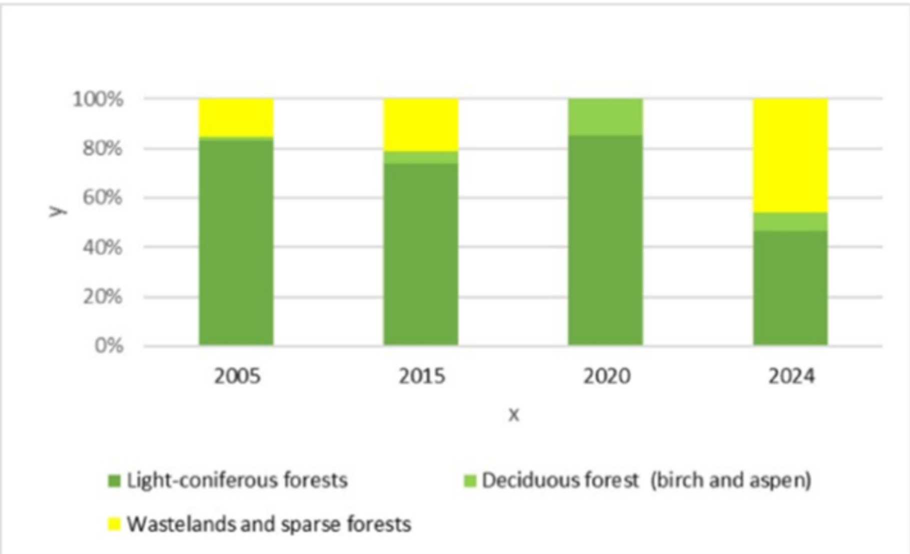


Figure 10. Natural Forest Regeneration in sample plot No. 4 from 2005 to 2024 (%).

Table 9. Dynamics of forest and vegetation changes in sample plot No. 3(m²) from 2005 to 2024.

Period	Light-coniferous forests	Deciduous forest (birch and aspen)	Wastelands and sparse forests
2005	61010	1100	11100
2015	48911	3378	13887
2020	56660	9616	89.5
2024	18500	2981	18195

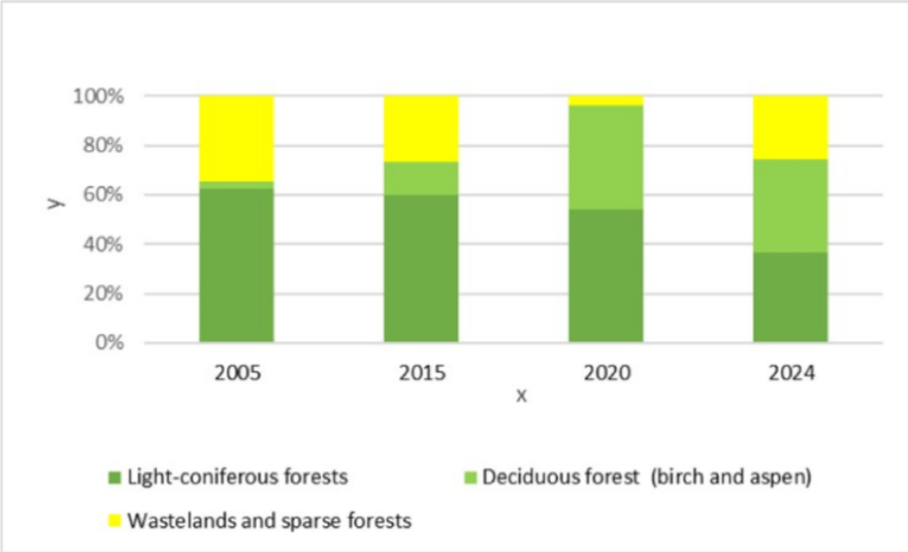


Figure 11. Natural Forest Regeneration in sample plot No. 3 from 2005 to 2024 (%).

Thus, the analysis of forest ecosystem recovery dynamics in Amankaragay validates the principles described in classical models of ecological succession. However, a more nuanced understanding of these processes necessitates an exploration of pyrogenic succession mechanisms in the context of established theoretical frameworks. The research supports the view that post-fire succession is not a linear process but may follow divergent trajectories influenced by factors such as fire intensity, climatic conditions, and landscape characteristics. In this regard, classical models of ecosystem dynamics, including the concept of alternative stable states [38] and the forest regeneration model following fires [39], are of particular relevance.

Restoration of forest ecosystems post-fire is a complex process governed by a multitude of factors, including forest type, fire intensity and scale, climatic conditions, and landscape features. Investigating these factors allows for a more comprehensive understanding of forest recovery dynamics, particularly within the context of the Amankaragay forest stands. Contemporary monitoring techniques, incorporating indices such as NDVI, NBR, and dNBR, enable objective assessments of vegetation damage and the trajectory of its regeneration. Pereira et al. demonstrated that NDVI is particularly effective for early-stage monitoring of post-fire vegetation recovery, whereas NBR more accurately quantifies the fire impact [40]. Zhang et al. showed that NBR and NDVI serve complementary roles, detecting severely burned areas and tracking long-term recovery trends [41]. These findings corroborate the work of Tokareva et al., who observed that the disparity between NDVI and NBR values in burned and unburned forests persists for up to 17 years post-fire, with these indices exhibiting a strong correlation with climatic variables [11].

Our study affirms the utility of NBR, dNBR, and NDVI indices for long-term monitoring of forest recovery following fire disturbances. Specifically, dNBR proved to be particularly informative in the analysis of post-fire changes occurring 20 years after the event: in areas affected by surface fires, the index values gradually reverted to background levels, whereas in regions impacted by crown fires, the values remained elevated, signifying deep structural alterations within the forest. NDVI data demonstrated that in areas affected by moderate surface fires, vegetation productivity approached baseline levels, while in crown fire areas, productivity remained significantly suppressed, underscoring differences in biomass accumulation rates and forest stand recovery.

The analysis of post-fire successional stages in Amankaragay reveals that the recovery patterns align with classical models of ecosystem dynamics. According to Ramensky, the recovery process progresses through predictable stages: herbaceous (1–5 years), shrub and young tree stages (up to 25 years), secondary broadleaf forest formation (40–60 years), and ultimate recovery of mature coniferous forests (120–150 years) [42]. These findings resonate with the work of Matveeva et al., who studied similar processes in coniferous-broadleaved forests in the Anyuy National Park [43].

Different restoration strategies can significantly affect the speed and success of forest regeneration. For instance, research at the Krasnoyarsk Scientific Center of the Siberian Branch of the Russian Academy of Sciences demonstrated that the application of fertilizers derived from conifer sawdust accelerates microbial processes in the soil, thereby enhancing pine forest recovery and increasing seedling numbers by 4–6 times [44]. Conversely, studies by Zhumadina and co-authors in the ribbon forests of the Irtysh region revealed that natural pine regeneration occurs unevenly, underscoring the need to consider terrain in the design of reforestation programs [45].

Studies by Turner et al. in Yellowstone National Park confirmed that crown fires can lead to a complete replacement of tree species, with pine forests being substituted by aspen communities, with recovery taking between 50 to 100 years [46]. Keeley and Pausas demonstrated that in Mediterranean and Californian ecosystems, crown fires lead to the formation of resilient shrubland landscapes, whereas surface fires foster the regeneration of coniferous species [47]. Therefore, the analysis of forest recovery dynamics in Amankaragay underscores that the velocity and direction of succession are influenced by multiple factors, including fire intensity, topography,

Table 10. Dynamics of forest and vegetation changes in sample plot No. 6 (m²) from 2005 to 2024.

Period	Light-coniferous forests	Deciduous forest (birch and aspen)	Wastelands and sparse forests
2005	49301	2500	27275
2015	47615	10807	21154
2020	42844	33632	3100
2024	29082	30056	20438

Figure 12. Natural Forest Regeneration in sample plot No. 6 from 2005 to 2024 (%).

climatic conditions, and restoration measures. The integrated use of satellite data and field observations facilitates not only the assessment of recovery rates but also the formulation of effective forest management strategies in the face of climate change.

4. CONCLUSIONS

The findings of this study highlight that the forests of Amankaragay possess significant potential for natural regeneration, which can optimize successional processes. Both remote sensing and field data provide crucial insights into the current state and future trajectory of forest ecosystems, essential for informed forest management and conservation decisions. Key conclusions include the impact of fire intensity and type on recovery rates, with crown fires slowing recovery due to severe canopy loss, while moderate -intensity fires support higher regeneration rates. The dNBR and NDVI indices have proven effective in monitoring forest recovery, enabling long-term, comprehensive assessments. Supervised image classification enhances the accuracy of ecosystem monitoring, aiding in forecasting future dynamics and guiding restoration strategies. Field data further validate remote sensing accuracy, improving the precision of recovery predictions. Additionally, biotic and abiotic factors such as soil moisture and light availability significantly influence recovery rates, with favorable conditions accelerating recovery. Finally, the integration of remote sensing and field studies is indispensable for forecasting ecosystem development, supporting adaptive management strategies and evidence-based conservation efforts, especially in the context of climate change and increasing fire disturbances.

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Conflicts of Interest

The authors declare no conflict of interest.

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REFERENCES

[1] M. A. Sofronov and A. V. Volokitina. (2007). "Methods of pyrological examination and description of forest areas covered by fires". *Sukachev Institute of Forestry.*

[2] M. Drüke, B. Sakschewski, W. von Bloh, M. Billing, W. Lucht, and K. Thonicke. (2023). "Fire may prevent future Amazon forest recovery after large-scale deforestation". *Communications Earth & Environment.* **4** (1). 10.1038/s43247-023-00911-5.

[3] R. Nedkov. (2018). "Quantitative Assessment Of Forest Degradation After Fire Using Ortogonalized Satellite Images From Sentinel -2". *Comptes rendus de l'Acade'mie bulgare des Sciences.* **71** (1): 83-86. 10.7546/grabs2018.1.11.

[4] M. I. Budyko.(1974)." Climate Change". Gidrometeoizdat, Leningrad.

[5] K. T. Davis, S. Z. Dobrowski, Z. A. Holden, P. E. Higuera, and J. T. Abatzoglou. (2018). "Microclimatic buffering in forests of the future: the role of local water balance". *Ecography.* **42** (1): 1-11. 10.1111/ecog.03836.

[6] G. I. Saucedo, R. Perucca, and D. Kurtz. (2023). "Las causas de los incendios de principios del año 2022 en la provincia de Corrientes". *Ecología Austral.* **33** (1): 273-284. 10.25260/ea.23.33.1.0.2020.

[7] T. A. Schroeder, M. A. Wulder, S. P. Healey, and G. G. Moisen. (2012). "Detecting post-fire salvage logging from Landsat change maps and national fire survey data". *Remote Sensing of Environment.* **122** : 166-174. 10.1016/j.rse.2011.10.031.

[8] S. Escuin, R. Navarro, and P. Fernández. (2007). "Fire severity assessment by using NBR (Normalized Burn Ratio) and NDVI (Normalized Difference Vegetation Index) derived from LANDSAT TM/ETM images". *International Journal of Remote Sensing.* **29** (4): 1053-1073. 10.1080/01431160701281072.

[9] S. A. Bartalev, E. A. Lupyan, F. V. Stytsenko, O. Y. Panova, and V. Y. Efremov. (2014). "Express mapping of damage to Russian forests by fires using Landsat satellite data". *Modern Problems of Remote Sensing of the Earth from Space.* **11** (1): 9-20.

[10] Ж. В. Атутова. (2024). "Опыт применения геоинформационных данных в оценке постпирогенного восстановления растительного покрова". *Вестник ВГУ. Серия: География. Геоэкология.* (3): 4-13. 10.17308/geo/1609-0683/2024/3/4-13.

[11] О. С. Токарева, А. Д. А. Алшаиби, and О. А. Пасько. (2021). "Оценка Восстановительной Динамики Растительного Покрова Лесных Гарей С Использованием Данных Со Спутников Landsat". *Izvestiya Tomskogo Politekhnicheskogo Universiteta Inziniring Georesursov.* **332** (7): 191-199. 10.18799/24131830/2021/7/3283.

[12] F. T. Zahura, G. Bisht, Z. Li, S. McKnight, and X. Chen. (2024). "Impact of topography and climate on post-fire vegetation recovery across different burn severity and land cover types through random forest". *Ecological Informatics.* **82**. 10.1016/j.ecoinf.2024.102757.

[13] J.-H. Ryu, K.-S. Han, S. Hong, N.-W. Park, Y.-W. Lee, and J. Cho. (2018). "Satellite-Based Evaluation of the Post-Fire Recovery Process from the Worst Forest Fire Case in South Korea". *Remote Sensing.* **10** (6). 10.3390/rs10060918.

[14] E. G. Shvetsov and E. I. Ponomarev. (2020). "Postfire Effects in Siberian Larch Stands on Multispectral Satellite Data". *Contemporary Problems of Ecology.* **13** (1): 104-112. 10.1134/s1995425520010096.

[15] P. G. Pugachev. (1994). "Pine forests of the Torgai depression". Kostanay Printing Yard, Kostanay.

[16] R. S. E. K. F. Enterprise. (2023). "Forest management project of KSU "Semiozerny Forestry Institution" of the Department of Natural Resources and Environmental Management of the Akimat of Kostanay region".

[17] C. H. Key and N. C. Benson. (2006). "Landscape assessment: Ground measure of severity, the Composite Burn Index; and remote sensing of severity, the Normalized Burn Ratio". *FIREMON: Fire effects monitoring and inventory system.*

[18] E. S. Kasischke, M. R. Turetsky, R. D. Ottmar, N. H. F. French, E. E. Hoy, and E. S. Kane. (2008). "Evaluation of the composite burn index for assessing fire severity in

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Alaskan black spruce forests". *International Journal of Wildland Fire.* **17** (4). 10.1071/wf08002.

[19] A. T. Hudak, P. Morgan, M. J. Bobbitt, A. M. S. Smith, S. A. Lewis, L. B. Lentile, P. R. Robichaud, J. T. Clark, and R. A. McKinley. (2007). "The Relationship of Multispectral Satellite Imagery to Immediate Fire Effects". *Fire Ecology.* **3** (1): 64-90. 10.4996/fireecology.0301064.

[20] C. J. Tucker. (1979). "Red and photographic infrared linear combinations for monitoring vegetation". *Remote Sensing of Environment.* **8** (2): 127-150. 10.1016/0034-4257(79)90013-0.

[21] J. W. Rouse, R. H. Haas, J. A. Schell, and D. W. Deering. (1974). "Monitoring vegetation systems in the Great Plains with ERTS. In NASA Goddard Space Flight Center". *Third Earth Resources Technology Satellite-1 Symposium.* 309-317.

[22] G. H. Mitri and I. Z. Gitas. (2013). "Mapping post-fire forest regeneration and vegetation recovery using a combination of very high spatial resolution and hyperspectral satellite imagery". *International Journal of Applied Earth Observation and Geoinformation.* **20** : 60-66. 10.1016/j.jag.2011.09.001.

[23] J. D. Miller and A. E. Thode. (2007). "Quantifying burn severity in a heterogeneous landscape with a relative version of the delta Normalized Burn Ratio (dNBR)". *Remote Sensing of Environment.* **109** (1): 66-80. 10.1016/j.rse.2006.12.006.

[24] A. Viana-Soto, I. Aguado, and S. Martínez. (2017). "Assessment of Post-Fire Vegetation Recovery Using Fire Severity and Geographical Data in the Mediterranean Region (Spain)". *Environments.* **4** (4). 10.3390/environments4040090.

[25] F. V. Stytsenko, S. A. Bartalev, A. V. Bukas, D. V. Ershov, and I. A. Saigin. (2019). "The possibilities of prolonged burnt severity assessment of evergreen coniferous forest using multi-spectral satellite data". *Sovremennye problemy distantsionnogo zondirovaniya Zemli iz kosmosa.* **16** (5): 217-227. 10.21046/2070-7401-2019-16-5-217-227.

[26] B. Liu, S. R. Biswas, J. Yang, Z. Liu, H. S. He, Y. Liang, M. K. Lau, Y. Fang, and S. Han. (2020). "Strong influences of stand age and topography on post-fire understory recovery in a Chinese boreal forest". *Forest Ecology and Management.* **473**. 10.1016/j.foreco.2020.118307.

[27] N. Stankova. (2023). "Post-Fire Recovery Monitoring Using Remote Sensing: A Review". *Aerospace Research in Bulgaria.* **35** : 192-200. 10.3897/arb.v35.e19.

[28] C. Yıldız, R. Çömert, H. Tanyaş, A. Yılmaz, A. Akbaş, S. S. Akay, Ö. Yetemen, and T. Görüm. (2023). "The effect of post-wildfire management practices on vegetation recovery: Insights from the Sapadere fire, Antalya, Türkiye". *Frontiers in Earth Science.* **11**. 10.3389/feart.2023.1174155.

[29] H. Lee, S. Kim, and J. Park. (2023). "Post-Fire Vegetation Recovery Assessment in Temperate Forests Using Time-Series MODIS Data and NDVI". *Forest Ecology and Management.* **512** : 120123.

[30] C. S. Stevens-Rumann and P. Morgan. (2019). "Tree regeneration following wildfires in the western US: a review". *Fire Ecology.* **15** (1). 10.1186/s42408-019-0032-1.

[31] J. T. Abatzoglou and A. P. Williams. (2016). "Impact of anthropogenic climate change on wildfire across western US forests". *Proceedings of the National Academy of Sciences.* **113** (42): 11770-11775. 10.1073/pnas.1607171113.

[32] L. V. Buryak and O. P. Kalenskaya. (2020). "The Impact of Wildfires on the Formation of Forest Stands in the Lower Angara Region".

[33] M. E. Chambers, P. J. Fornwalt, S. L. Malone, and M. A. Battaglia. (2016). "Patterns of conifer regeneration following high severity wildfire in ponderosa pine – dominated forests of the Colorado Front Range". *Forest Ecology and Management.* **378** : 57-67. 10.1016/j.foreco.2016.07.001.

[34] E. Chuvieco, L. Giglio, and C. Justice. (2008). "Global characterization of fire activity: toward defining fire regimes from Earth observation data". *Global Change Biology.* **14** (7): 1488-1502. 10.1111/j.1365-2486.2008.01585.x.

[35] J. Luoranen, J. Riikonen, and T. Saksa. (2022). "Factors affecting winter damage and recovery of newly planted Norway spruce seedlings in boreal forests". *Forest Ecology and Management.* **503**. 10.1016/j.foreco.2021.119759.

[36] S. Dupire, T. Curt, S. Bigot, and T. Fréjaville. (2019). "Vulnerability of forest ecosystems to fire in the French Alps". *European Journal of Forest Research.* **138** (5): 813-830. 10.1007/s10342-019-01206-1.

[37] N. S. Gamova, E. A. Faronova, Y. N. Korotkov, T. S. Koshovsky, and T. E. Yazrikova. (2023). "Early stages of pyrogenic succession in fir forests of the Southern Baikal Region (Baikal Reserve)". *Ecosystems: Ecology and Dynamics.* **7** (20): 113-136.

[38] C. S. Holling. (1973). "Resilience and Stability of Ecological Systems". *Annual Review of Ecology and Systematics.* **4** (1): 1-23. 10.1146/annurev.es.04.110173.000245.

[39] M. G. Turner, W. H. Romme, D. B. Tinker, and D. R. Foster. (2016). "The landscape ecology of fire". *Annual Review of Ecology, Evolution, and Systematics.* **47** : 1-19. 10.1146/annurev-ecolsys-121415-032141.

[40] S. Wang, X. Song, Q. Chen, X. Wang, M. Wei, Y. Ke, and Z. Luo. (2020). "Mechanical properties of cemented tailings backfill containing alkalized rice straw of various lengths". *Journal of Environmental Management.* **276** : 111124. 10.1016/j.jenvman.2020.111124.

[41] D. Rodriguez-Cubillo, N. A. L. Pilon, and G. Durigan. (2021). "Tree height is more important than bark thickness, leaf habit or habitat preference to survive fire in the cerrado of south-east Brazil". *International Journal of Wildland Fire.* **30** (11): 899-910. 10.1071/wf21091.

[42] L. G. Ramenskiy, I. A. Tsatsenkin, O. N. Chizhikov, and N. A. Antipov. (1994)." Ecological assessment of forage lands by vegetation cover". Selhozgiz, Moscow.

[43] А. Л. Гребенюк, Р. С. Великий, and А. Г. Матвеева. (2023). "Послепожарная Сукцессия В Хвойно-Широколиственных Лесах Национального Парка "Анюйский"". *Сибирский лесной журнал.* **6** : 85-97. 10.15372/sjfs20230609.

[44] M. Simiele, E. De Zio, A. Montagnoli, M. Terzaghi, D. Chiatante, G. S. Scippa, and D. Trupiano. (2022). "Biochar and/or Compost to Enhance Nursery-Produced Seedling Performance: A Potential Tool for Forest Restoration Programs". *Forests.* **13** (4). 10.3390/f13040550.

[45] S. Zhumadina, J. Chlachula, A. Zhaglovskaya-Faurat, J. Czerniawska, G. Satybaldieva, N. Nurbayeva, N. Mapitov, A. Myrzagaliyeva, and E. Boribay. (2021). "Environmental Dynamics of the Ribbon-Like Pine Forests in the Parklands of North Kazakhstan". *Forests.* **13** (1). 10.3390/f13010002.

[46] M. G. Turner, K. H. Braziunas, W. D. Hansen, and B. J. Harvey. (2019). "Short-interval severe fire erodes the resilience of subalpine lodgepole pine forests". *Proceedings of the National Academy of Sciences.* **116** (23): 11319-11328. 10.1073/pnas.1902841116.

[47] J. G. Pausas and J. E. Keeley. (2021). "Wildfires and global change". *Frontiers in Ecology and the Environment.* **19** (7): 387-395. 10.1002/fee.2359.