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Research Article

Natural restoration of forests after a fire in the Amankaragay Forest Massif of the Kostanay Region, Republic of Kazakhstan

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Abstract

The article presents the results of an analysis of natural forest regeneration after a wildfire in the Amankaragay Forest Massif, Kostanay Region, Republic of Kazakhstan, during the post-fire period. The forest landscapes of the Kostanay Region are subject to pyrogenic impacts of both natural and anthropogenic origin, leading to changes in the phytocenosis of ecosystems. The study integrates field research findings with remote sensing data and methods (dNBR, NBR, NDVI) to assess post-fire conditions and forest regeneration in the Kostanay Region through the comparison of three sample plots. Changes in summer dNBR values indicate the severity of the fire, while annual and seasonal variations in NDVI values, particularly during the summer, reflect the intensity and level of post-fire forest recovery. The analysis of natural forest regeneration after the wildfire in the Amankaragay Forest Massif was conducted using field research methods, ArcGIS 10.8 software, and spectral index analysis of multi-temporal high- and medium-resolution satellite imagery. Based on the research objectives and the specific characteristics of the study area, necessary calculations and analyses were conducted for each sample plot. As a result, the natural regeneration of forest landscapes was assessed, and relevant findings were obtained. Fire intensity and type determine the rate of forest recovery. dNBR and NDVI indices confirm the effectiveness of remote sensing for monitoring post-fire forest recovery. Remote sensing data and field assessments enable not only the evaluation of current forest conditions but also predictions of future development. The changes in the structure of dominant tree species in the Amankaragay massif, detected through satellite monitoring after exposure to the pyrogenic factor, were verified using field research methods.

Key words: dNBR, natural regeneration, NDVI, pyrogenic factor, remote sensing

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1. Introduction

Wildfires are an integral part of natural processes, leading to significant transformations in ecosystems. They cause alterations in vegetation cover, disrupt the ecological balance of phytocenoses, and affect both the qualitative and quantitative composition of species populations in fire-damaged areas (Sofronov and Volokitina 2007; Nedkov 2018; Drüke et al. 2023). As a result of wildfires, changes occur in species composition, soil structure, hydrological regimes, and the microclimate of affected regions (Davis et al. 2019; Saucedo et al. 2023).

However, after a fire event, the process of natural forest regeneration begins, which depends on multiple factors, including fire intensity and extent, forest type, climatic conditions, and the availability of a seed bank (Stevens-Rumann and Morgan 2019). The dynamics of wildfire occurrence in forest ecosystems are also correlated with climate warming projections (Budyko 1974).

Wildfires can originate from both natural processes and human activities. In recent years, their frequency and extent have increased significantly, primarily due to anthropogenic factors (Chuvieco et al. 2008; Abatzoglou and Williams 2016).

In recent decades, the frequency of wildfires has been increasing due to intensified land use, population growth, and rising recreational pressure on forests (Harvey et al. 2016; Chambers et al. 2016; Dupire et al. 2019). Moreover, this trend is closely linked to climate change projections, which suggest a higher likelihood of extreme fire events (Davis et al. 2019).

Given these challenges, contemporary scientific research increasingly focuses on developing effective strategies for restoring fire-affected forest ecosystems and analyzing post-fire vegetation recovery dynamics. Remote sensing methods, in combination with field-based research, provide a powerful approach for assessing vegetation regeneration on burned areas, offering scientifically grounded data for informed decision-making in forest restoration efforts (Schroeder et al. 2012; Saucedo et al. 2023; Ruggirello et al. 2023).

Currently, numerous scientific studies focus on post-fire forest regeneration and the assessment of vegetation cover dynamics using both field and remote sensing methods, including the Normalized Burn Ratio (NBR), the Normalized Difference Vegetation Index (NDVI), and others. The works of Escuin et al. (2008), Bartalev et al. (2014), Ryu et al. (2018), Shvetsov and Ponomarev (2020), Tokareva et al. (2021), Atutova (2024), Zahura et al. (2024) are dedicated to analyzing and evaluating natural forest regeneration in the post-fire period. These studies emphasize the importance of spectral indices and modern technologies for monitoring and predicting forest recovery after wildfires. The NDVI, along with other spectral indices, is one of the most widely used and effective methods for assessing forest damage, rehabilitation, and destruction.

In recent decades, large-scale field research has become increasingly challenging due to logistical constraints and significant financial costs. Consequently, integrating remote sensing methods with field studies for analyzing the dynamics of natural vegetation recovery provides more reliable and comprehensive results. Information on wildfire dynamics, damage severity, and vegetation recovery helps predict future developments and implement appropriate preventive measures. Such studies enable the assessment of the impact of different fire types on ecosystem dynamics.

This study aims to analyze the natural regeneration of forests after a wildfire in the Amankaragay Forest Massif, Republic of Kazakhstan. The research involves a comparative analysis of three sample plots using remote sensing and field data: (i) a sample plot affected by a moderate-severity crown fire; (ii) a sample plot affected by a moderate-severity surface fire; (iii) a control (unburned) sample plot.

2. Materials and methods

2.1. Study area and research object

During the field study, sample plots №3 (control), №4 and №6 (burned areas) were examined (Table 1). These plots are located in the northeastern part of the Amankaragay Forest Massif in the Kostanay Region, an area with a high risk of wildfires.

Table 1. Data on the investigated research plots.

№ sample plots	Names of forestry enterprises	Name of the forestry district	Coordinates	Forest Quarter	Forest compartment number	Time of the fire
6	Semiozerskoye	Novonezhinsky	52°27′19.50″ N 64°26′17.24″ E	20	1	control
4	Semiozerskoye	Novonezhinsky	52°30′47.54″ N 64°5′26.08″ E	9	11	2004
3	Semiozerskoye	Novonezhinsky	52°30′24.12″ N 64°4′0.61″ E	7	22	2004

The selection of sample plots was based on the following criteria: areas affected by wildfires of varying intensity and severity. Long-unburned areas to assess natural forest regeneration processes. Availability of a sufficient number of high-quality, cloud-free archival satellite images spanning the longest possible period (up to 20 years) to accurately determine the timing of fire events.

The Amankaragay pine forest is the largest insular relict forest massif in the Kostanay Region, consisting of a mixed composition of tree species, including birch (*Betula pendula*), aspen (*Populus tremula*), and Scots pine (*Pinus sylvestris*) (Fig. 1). It holds significant recreational and ecological value, particularly in climate regulation.

The forest extends across the southern part of the Kostanay (North-Turgay) Plain, spanning approximately 45 km in length and 14.5 km in width. As of 2024, the total forested area covers about 32,000 hectares.

In 2022, a large wildfire in the Auliekol district of the Kostanay Region burned approximately 43,000 ha of forest, with a significant portion of the affected area belonging to the Amankaragay pine forest. The dominant tree species is Scots pine (*Pinus sylvestris*), which forms pine-dominated stands on sandy soils. Birch and aspen forests are mainly found in the lower parts of sandy ridges and are often adjacent to the shores of saline lakes. Shrub willows (*Salix spp.*) typically grow along riverbanks and lake shores, while wild roses (*Rosa spp.*) and meadowsweet (*Filipendula spp.*) are common in ravines and on slopes. The study of the Amankaragay Forest Massif provides a unique opportunity to assess the long-term impacts of wildfires and their influence on forest ecosystems under continental climatic conditions (Pugachev 1994).

The increasing frequency and extent of pyrogenic disturbances in natural systems in recent decades are closely linked to both climatic and anthropogen-

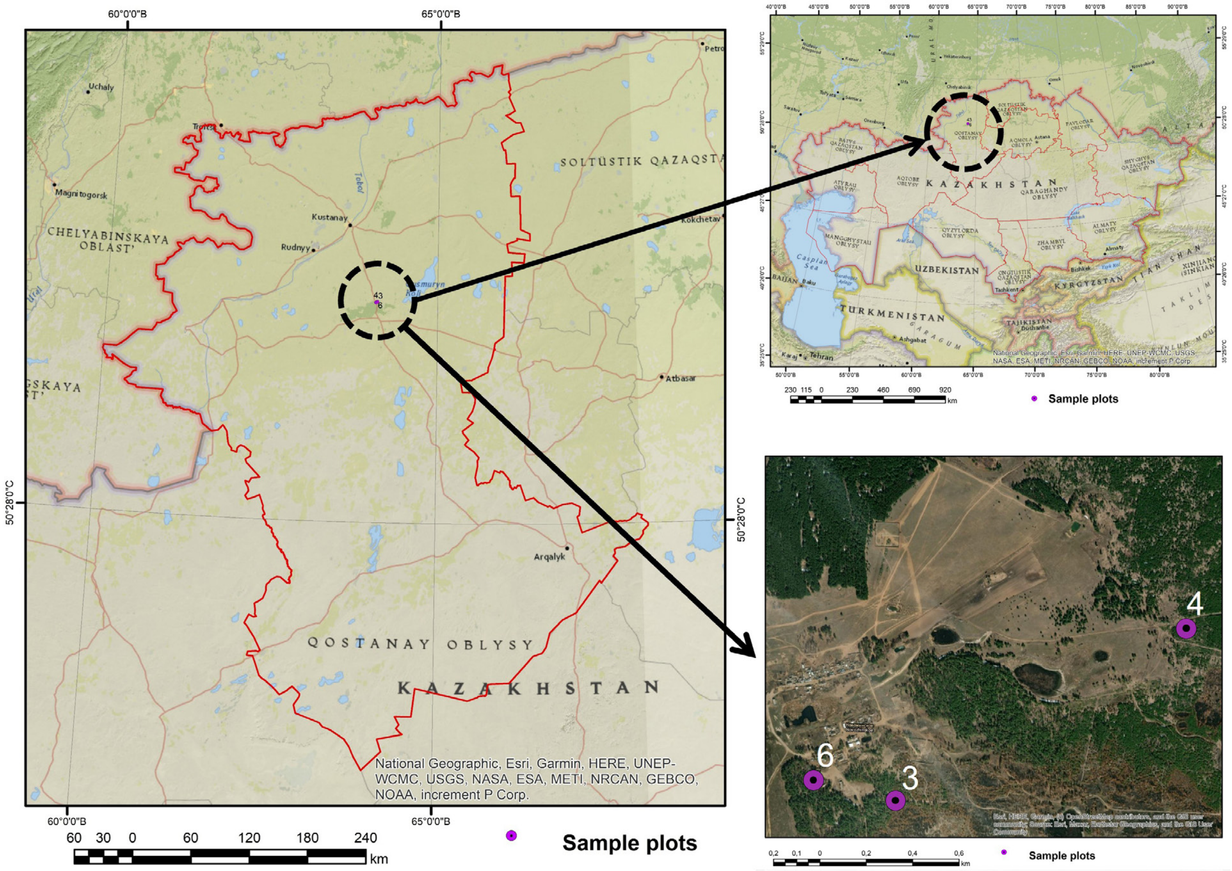

Figure 1. Amankaragay Forest Massif, Kostanay Region.

ic factors. The study area is characterized by arid growing conditions. According to the forest fire zoning classification, the area falls within the Amankaragay fire-prone region, where the fire-hazardous period lasts approximately 208 days per year.

Between 2001 and 2024, a total of 88 forest fire incidents were recorded within the forest management area, affecting 5,249.9 ha, including 5,010.7 ha of forested land, which comprises both natural stands and cultivated plantations (RSE "Kazakh Forestry Enterprise" 2023).

The climate of the region, located in the center of the Eurasian continent and significantly distant from large bodies of water, is sharply continental. It is characterized by hot, dry summers and cold, low-snow winters. Low winter temperatures and high summer temperatures, combined with droughts, dry winds, dust storms, as well as late spring and early autumn frosts, negatively impact the growth and development of woody and shrub vegetation.

Sample Plot №6 is located in Compartment 1, Quarter 20 of the Novonezhinsky Forestry Division, part of the Semiozerskoye Forestry Enterprise. The total area of the forest compartment is 9.2 ha. Based on its protection category, this plot is classified as a field- and soil-protective forest. The stand consists of natural forest plantations, with an average stand age of 93 years.

The sample plot №6 was selected as a control plot, representing an unburned forest area. It serves as a baseline for assessing natural forest conditions, as it has not been affected by fire. The dominant tree species is Scots pine (*Pinus* *sylvestris*) of natural origin, with occasional silver birch (*Betula pendula*) present as an accompanying species. The shrub layer is moderately developed and includes rowan (*Sorbus aucuparia*), Tatar honeysuckle *(Lonicera tatarica*), and wild rose (*Rosa spp.*). The herbaceous layer comprises lingonberry (*Vaccinium vitis-idaea*), bilberry (*Vaccinium myrtillus*), fireweed (*Chamaenerion angustifolium*), and various grasses (*Poa spp., Calamagrostis spp.*). Additionally, mosses and lichens (*Pleurozium schreberi, Cladonia spp.*) are present, contributing to soil stability and moisture retention.

Sample plot №4 (Fig. 2) is located in Compartment 11, Quarter 9 of the Novonezhinsky Forestry Division under the Semiozernoye Forestry Enterprise in the Kostanay Region.

At the burned plot of sample plot №4, a young mixed forest has formed, with pine as the dominant species, temporary dominance of deciduous trees, and a well-developed herb-shrub layer. The shrub layer is represented by *Sorbus aucuparia* (rowan), *Lonicera tatarica* (Tatar honeysuckle), and *Rosa spp.* (wild rose). The herbaceous layer includes *Spiraea crenata* (crested spiraea), Poaceae (bluegrasses), *Vaccinium vitis-idaea* (lingonberry), *Vaccinium myrtillus* (bilberry), *Chamaenerion angustifolium* (fireweed), and various grasses (*Poa spp., Calamagrostis spp*.). Additionally, mosses and lichens, such as *Pleurozium schreberi* and *Cladonia spp.*, are present.

Sample plot №3 is located in Compartment 1, Quarter 20 of the Novonezhinsky Forestry, part of the Semiozyornoye Forestry Enterprise. A heterogeneous, multi-aged Scots pine (*Pinus sylvestris*) stand has developed here, characterized by abundant natural regeneration and well-established shrub and herbaceous layers. Scots pine remains the dominant tree species, as some mature individuals survived the fire, ensuring continuity in stand composition. The shrub layer includes rowan (*Sorbus aucuparia*), Tatar honeysuckle (*Lonicera tatarica*), wild rose (*Rosa spp.*), and alder buckthorn (*Frangula alnus*). The herbaceous layer consists of lingonberry (*Vaccinium vitis-idaea*), bilberry (*Vac-*

Figure 2. Sample plot № 4.

cinium myrtillus), various grasses (*Poa spp.*, *Calamagrostis spp.*), cotoneaster (*Cotoneaster spp.*), and early sedge (*Carex praecox*).

2.2 Data and methods

The article compiles and systematizes materials for analyzing natural forest regeneration in the post-fire period. The study utilized high- and medium-resolution satellite imagery from Landsat 8, Landsat 7, and Sentinel-2, as well as data from the National Aeronautics and Space Administration Goddard Space Flight Center (2025), the U.S. Geological Survey archive (2025), and JSC "NC Kazakhstan Gharysh Sapary" (2025) for the period from 2003 to 2024.

The algorithm for analyzing the natural regeneration of forests in the Kostanay Region after a wildfire is presented in Fig. 3.

Field investigations were conducted to assess natural forest regeneration following wildfires. The research included identifying tree species composition

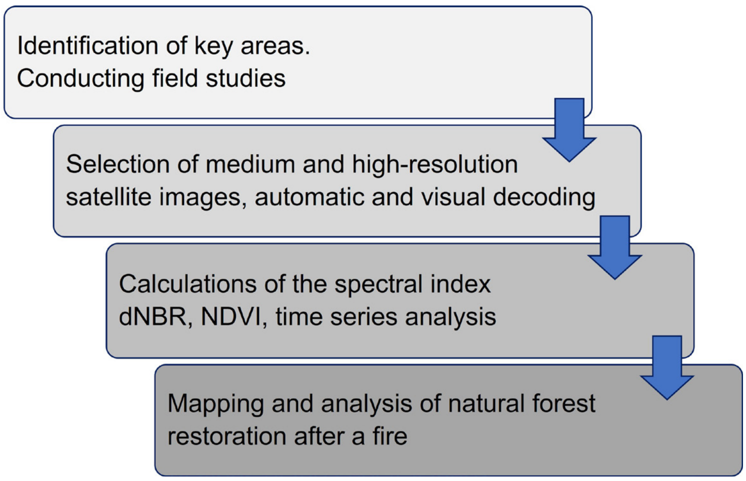

Figure 3. Algorithm for analyzing the natural restoration of forests after a fire.

and their proportions, evaluating seedling condition, measuring seedling height and diameter, and estimating seedling density per hectare.

To analyze burn area dynamics and assess the degree of fire disturbance, the NBR and (dNBR) were applied (Key and Benson 2006; Kasischke et al. 2008).

Currently, numerous spectral indices are used to estimate wildfire-affected areas, but the NBR is among the most widely utilized (Miller and Thode 2007). The primary criterion for identifying burn scars is a decrease in spectral reflectance in the near-infrared (NIR) region of the spectrum.

The NBR is calculated using the eq. 1:

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

where BNIR and BSWIR are the spectral bands of multispectral satellite imagery within the 0.75–0.90 μm and 2.09–2.35 μm ranges, respectively. The NBR index is based on the relationship between near-infrared (NIR) and shortwave infrared (SWIR) reflectance. The NIR band is highly sensitive to chlorophyll loss in vegetation, while the SWIR band responds strongly to changes in vegetation moisture content.

To quantitatively assess fire impact on the study area, the dNBR was applied. This index is derived from the difference between pre-fire and post-fire NBR values using satellite imagery from Landsat 7, Landsat 8, and Sentinel-2. The dNBR serves as a modification of the NBR and is calculated using the eq. 2:

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

Where NBRprefire represents the NBR value calculated before the wildfire, and NBRpostfire is the NBR value computed after the wildfire.

Based on this equation, areas with pixel values near or equal to 0 indicate unburned regions, while values closer to 1 correspond to severely burned areas. The dNBR spectral index is highly sensitive to variations in leaf moisture content and chlorophyll levels. Classification of Burn Severity based on dNBR values: above 0.66—high level of post-fire disturbance; from 0.66 to 0.27—a moderate level of post-fire disturbance; from 0.27 to 0.1—a low level of post-fire disturbance; below 0.1—no fire or post-fire disturbances (Key and Benson 2006).

The assessment of forest vegetation conditions in disturbed areas is effectively reflected by the NDVI (Tucker 1979), a relative measure of the amount of photosynthetically active biomass (Rouse et al. 1974; Hudak et al. 2008; Escuin et al. 2008).

The NDVI value depends on the total vegetation biomass and ranges from -1 to 1. The NDVI and other spectral indices are among the most widely used tools for analyzing changes in the quantitative and qualitative composition of forests (Stytsenko et al. 2019; Liu et al. 2020; Stankova 2023; Yıldız et al. 2023; Atutova 2024). When integrated with field-based methods, these indices provide reliable and high-quality results.

The NDVI is calculated using the eq. 3:

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

Where NIR and RED represent the spectral bands of multispectral satellite imagery obtained from Landsat 7, Landsat 8, and Sentinel-2.

The values of NBR and NDVI show a strong correlation with field assessments of burned areas. These indices are widely used by the U.S. Forest Service for the practical evaluation of wildfire-induced forest damage (Stevens-Rumann and Morgan 2019), the delineation of recent burn scars, and the assessment of fire severity across different vegetation zones (Table 1). The vegetation recovery assessment scale is presented in Table 2 (Rouse et al. 1974; Hudak et al. 2008).

Table 2. Relationship between NDVI and vegetation cover condition.

NDVI value	Vegetation biomass development level
0.00–0.20	Absence of vegetation
0.20–0.31	Low biomass development
0.30–0.60	Moderate biomass development
0.60–1.00	High biomass development

3. Results

The vegetation recovery in the studied areas depends on the fire intensity and the degree of pyrogenic transformation of the natural environment. In 2004, fires of various types and intensities occurred in sample plots №3 and №4, according to reports from the Semiozernoe Forestry of Kostanay Region, Republic of Kazakhstan, as well as data from JSC “NC Kazakhstan Gharysh Sapary”, the NASA Goddard Space Flight Center, and the archive of the U.S. Geological Survey.

Using remote sensing and field methods, including the calculation of NBR, dNBR, and NDVI indices, we identified burned areas from the 2004 fire in sample plots №3 and №4 of the Amankaragay Massif (Fig. 4A). The analysis of NBR for 2003 (pre-fire) and 2005 (post-fire) confirmed that by 2005, the burned area had fully encompassed sample plots №4 and №3 (Figs 4A–C). These findings were validated through field studies conducted between 2022 and 2024.

The results of the dNBR spectral index calculations showed that in 2005, the dNBR values for sample plot №6 ranged from -0.13 to -0.07, indicating areas unaffected by fire.

This is confirmed by field studies and justifies the selection of this sample plot as a control plot. The dNBR values for sample №3 plot range from 0.29 to 0.39, indicating a moderately low level of fire disturbance. The dNBR values for sample plot №4 range from 0.45 to 0.60, corresponding to a moderately high level of fire disturbance.

The dNBR spectral index data confirm the validity of selecting sample plots №6, №3, and №4 to compare the dynamics of natural forest regeneration.

Our analysis of the spectral dNBR values for the studied sample plots was also validated using the NDVI index, which showed values close to zero or negative in areas severely affected by the pyrogenic factor.

A temporary sample plot №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 №4 corresponds to its age, demonstrating good annual growth, with no observed pest or disease damage.

The area 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 condition and composition of tree vegetation in the burned area of sample plot №4 are presented in Table 3 and Fig. 5.

The proportion of Scots pine (*Pinus sylvestris*) in the tree species composition ranges from 50% to 70%, with an average of 60%, making it the dominant species typical of boreal forests and stable ecosystems. Scots pine exhibits high fire resistance and effectively regenerates after surface fires.

The proportion of silver birch (*Betula pendula*) in the regenerating forest ranges from 20% to 30%, with an average of 25%. Birch is a characteristic pioneer species that rapidly colonizes burned and disturbed areas. Due to its relatively short life cycle, it is gradually replaced by coniferous species over time.

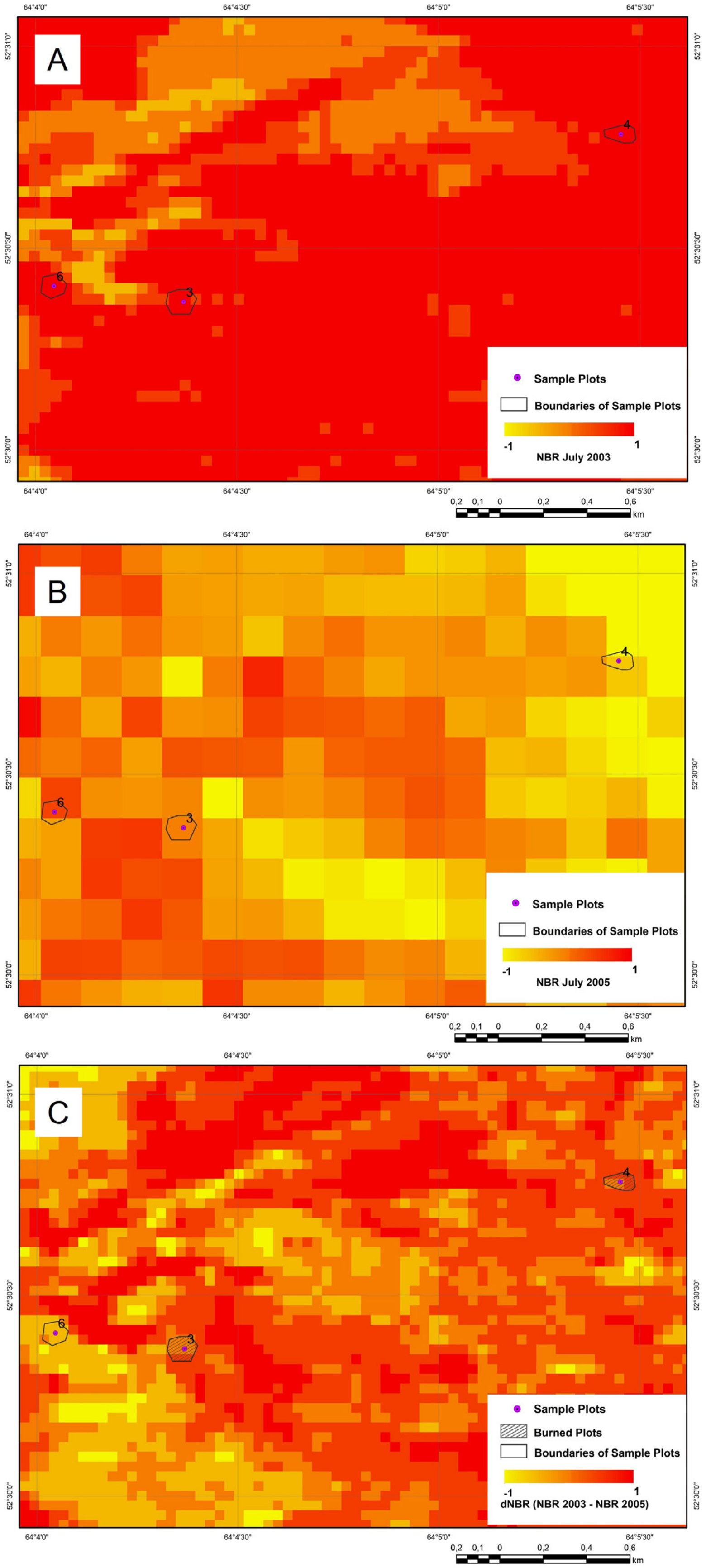

Figure 4. NBR index on sample plots №3, №4, and №6. **A** July 2003 **B** July 2005 **C** dNBR (NBR 2003–NBR 2005).

Table 3. Composition and characteristics of tree species in the burned area of sample plot №4.

Tree species	Height (m)	Diameter (cm)	Percentage composition (%)
Scots pine (*Pinus sylvestris*)	5–8	8–15	50–70
Silver birch (*Betula pendula*)	8–12	10–20	20–30
Aspen (*Populus tremula*)	10–15	10–25	5–10
Willow (*Salix spp.*)	3–5	5–10	up to 5

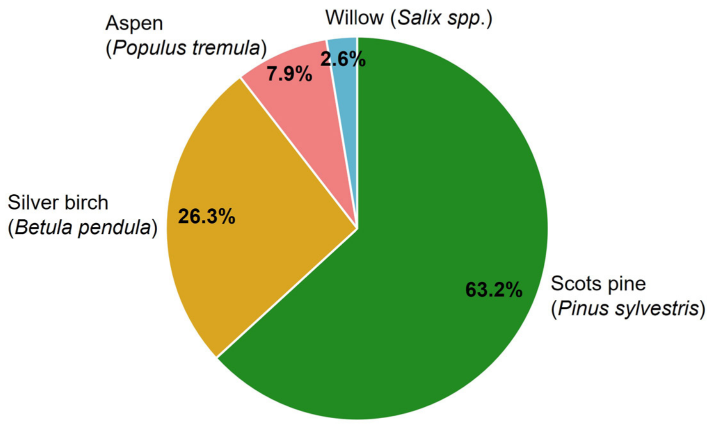

Figure 5. Tree species composition on sample plot №4.

Aspen (*Populus tremula*) constitutes 5–10% of the forest composition, with an average of 7.5%. It is also a pioneer species, distinguished by its ability for rapid vegetative reproduction. Aspen is commonly found in moist areas and plays a significant role in the early stages of forest regeneration.

The proportion of willow (*Salix spp.*) in the tree species composition does not exceed 5%, with an average of 2.5%. Willows typically grow in floodplain environments, along watercourses, and in waterlogged areas. They contribute to the initial stages of ecosystem recovery but do not form stable forest stands.

The pine regeneration consists of trees at various developmental stages, established through natural seed dispersal and recruitment (Table 4).

The total density of Scots pine (*Pinus sylvestris*) regeneration on the plot is 3,000–7,000 seedlings/ha, while the density of silver birch (*Betula pendula*) is 2,000–5,000 seedlings/ha. However, these values vary depending on plot conditions. In drier areas with higher competition from grasses, regeneration density is lower. In contrast, areas where the ash layer was less compact and decomposed more rapidly exhibit higher regeneration density.

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

Development stage	Age (years)	Height (m)	Diameter (cm)	Density (thousand trees/ha)
Seedlings	1–2	0.1–0.2	<1	1–2
Saplings	3–5	0.2–0.5	<1	3–5
Young stand	6–10	0.5–2	1–5	2–3
Understory	11–20	2–8	5–15	1.5–2

The growth dynamics of tree regeneration on burned areas are characterized by increased light availability, enhanced access to mineral nutrients, and reduced competition for resources in open spaces. In general, the burned area of sample plot №4, which resulted from a moderate-intensity crown fire in 2004, has developed favorable conditions for natural forest recovery. Field studies confirm the presence of healthy tree regeneration, indicating that post-fire recovery processes in the studied area have not been significantly disrupted.

An analysis of NDVI trends during the summer growing seasons from 2005 to 2024 demonstrates a steady increase, reflecting vegetation recovery (Fig. 7A–E). In 2004, sample plot №4 suffered significant fire damage, as indicated by dNBR values ranging from 0.45 to 0.60. By 2005, the NDVI value for the study area was 0.44, decreasing to 0.42 by 2010, which indicates sparse vegetation cover. Over the following years, the index steadily increased: 0.71 in 2015 and 0.80 in 2024, reflecting the successful natural regeneration of tree vegetation. Since 2010, rapid natural regeneration has been observed due to the establishment of fast-growing grasses and shrubs (*Chamaenerion angustifolium, Poaceae, Sorbus aucuparia*), leading to an increase in NDVI to 0.3–0.4, though still below mature forest levels. By 2020–2024 (16–20 years post-fire), the active growth of deciduous species (*Betula pendula*, *Populus tremula*, *Salix spp.*) resulted in a further increase in NDVI to 0.5–0.6. Concurrently, natural regeneration of *Pinus sylvestris* accelerated, promoting further afforestation of burned areas and a gradual convergence of vegetation characteristics with those of natural forests.

The analysis of NDVI data, correlated with field assessments, confirms the active natural regeneration of vegetation on the burned plot, facilitated by the development of tree regeneration and the establishment of herbaceous and shrub layers.

As of 2024, burned sample plot №4 in Amankaragai exhibits active Scots pine forest recovery. The dominant tree species remains *Pinus sylvestris*, while *Betula pendula* and *Populus tremula* are temporarily present in the stand composition. The height of Scots pines has reached 5–8 m, with a density ranging from 3,000 to 10,000 seedlings/ha. The herbaceous cover has stabilized, a moss layer has formed, and the ecosystem is approaching its pre-fire state. It should be noted that the predominance of Scots pine indicates the establishment of a stable coniferous-deciduous forest. The high proportion of birch and aspen reflects the post-fire or disturbed nature of the ecosystem, where pioneer species play a crucial role in the early stages of forest regeneration.

A temporary sample plot №3 was established in the study area to assess recovery after the 2004 wildfire. That year, a moderate-intensity surface fire affected the burned area of sample plot №3. The structure and condition of the tree vegetation are presented in Table 5 and Fig. 6.

Table 5. Composition and characteristics of tree species in the burned area of sample plot №3.

Tree species	Height (m)	Diameter (cm)	Percentage composition (%)
Scots pine (*Pinus sylvestris*)	8–12	15–25	70–85
Silver birch (*Betula pendula*)	6–10	10–15	10–15
Aspen (*Populus tremula*)	8–12	10–20	5–10
Willow (*Salix spp.*)	3–5	5–10	up to 5

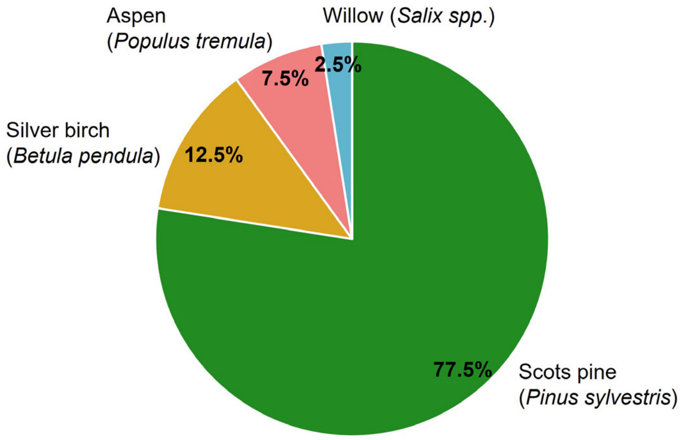

Figure 6. Tree species composition on sample plot №3.

The proportion of Scots pine (*Pinus sylvestris*) ranges from 70% to 85%, indicating its dominance and the formation of a stable coniferous stand. A high percentage of Scots pine is typical of resilient boreal forests and confirms its strong capacity for natural regeneration after wildfires. The proportion of silver birch (*Betula pendula*) suggests the presence of secondary tree species that play a crucial role in the early stages of succession. Birch acts as a pioneer species; however, its relatively low percentage compared to pine indicates the gradual restoration of a coniferous forest. The proportion of aspen (*Populus tremula*) varies between 5% and 10%, confirming its role in the initial stages of forest recovery. Aspen spreads effectively through vegetative reproduction but is gradually replaced by Scots pine and other more stable tree species.

The proportion of willow (*Salix spp.*) does not exceed 5%, indicating its localized distribution, primarily in waterlogged areas. Its minimal representation suggests a limited influence on stand formation.

Post-fire forest regeneration is actively progressing due to natural seed dispersal and the presence of surviving parent trees, which facilitate seedling establishment and growth (Table 6).

Damage to young forest stands is caused by various factors: (i) insects—the primary pests include the pine silk moth (*Dendrolimus pini*), which causes needle defoliation, and bark beetles (*Ips spp.*), whose activity remains low due to the overall stability of the forest; (ii) wild animals—roe deer, wild boars, and rodents damage the root systems and bark of trees, as well as loosen the soil. While this can slow the growth of young trees, it also facilitates seedling establishment; (iii) climatic factors—the main environmental stressor is drought, which leads to tree top dieback.

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

Development stage	Age (years)	Height (m)	Diameter (cm)	Density (thousand trees/ha)
Seedlings	1–2	0.1–0.2	<1	2–4
Saplings	3–5	0.3–0.7	<1	4–6
Young stand	6–10	1–3	2–6	3–5
Understory	11–20	3–10	6–15	2–4

The total density of Scots pine (*Pinus sylvestris*) regeneration in the study area is estimated at 5,000–9,000 seedlings/ha, while silver birch (*Betula pendula*) regeneration density ranges from 2,000 to 4,000 seedlings/ha. However, these values vary depending on plot conditions. In drier areas, where competition from herbaceous vegetation is higher, regeneration density is lower. The presence of a surviving parent stand has contributed to a higher regeneration density compared to areas affected by crown fires, ensuring a continuous seed source.

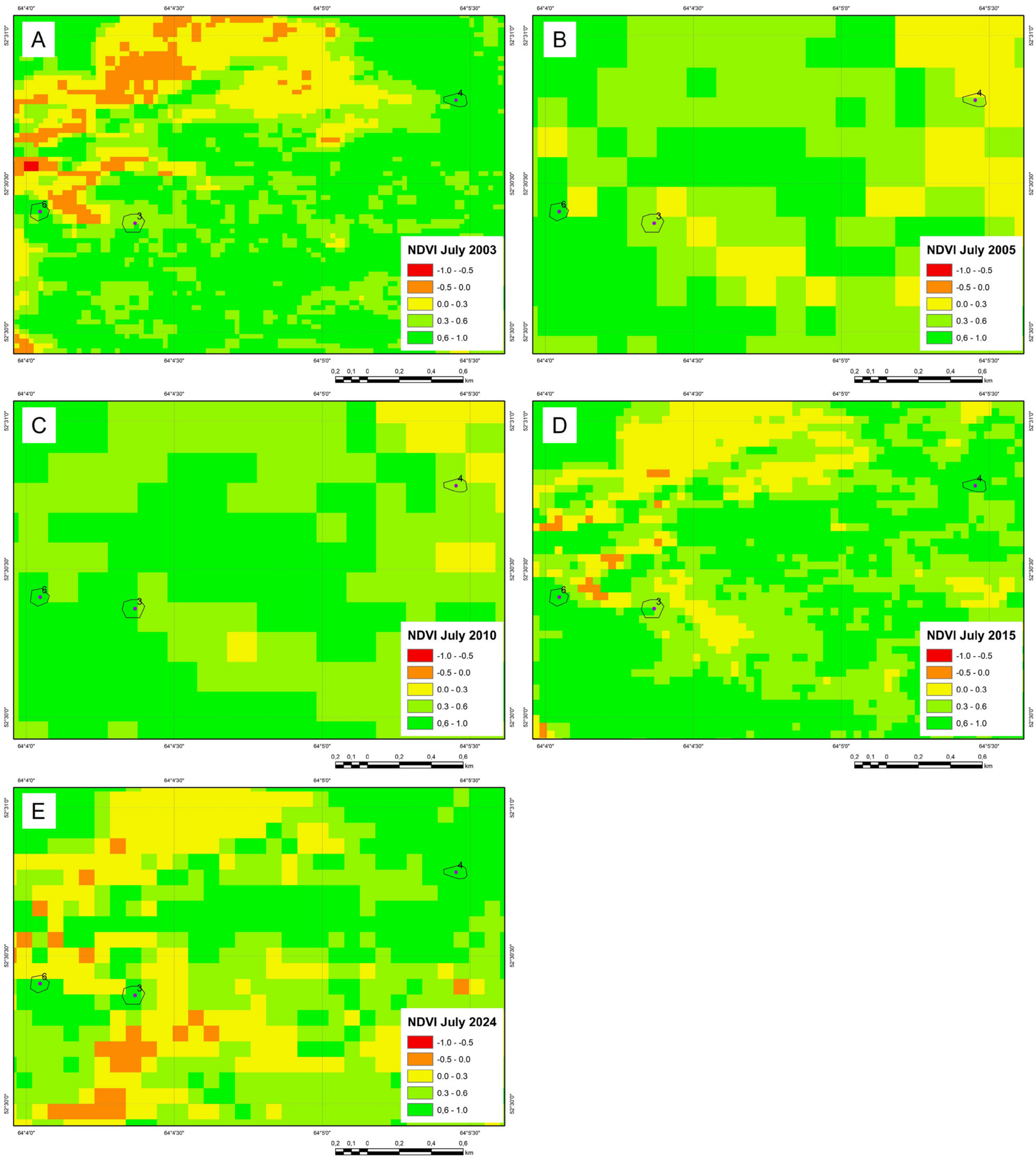

Figure 7. NDVI values on sample plots № 6, №3, and № 4 in the Amankaragay Forest Massif. **A** July 2003 **B** July 2005 **C** July 2010 **D** July 2015 **E** July 2024.

An analysis of NDVI trends for the burned area of sample plot №6 during the 2005–2024 summer growing seasons reveals a steady increase in vegetation index values, indicating progressive recovery. In 2004, following a moderate-intensity surface fire, the plot exhibited dNBR values ranging from 0.29 to -0.39, indicating moderate disturbance to the vegetation cover. By 2005, the NDVI value was 0.44, and by 2010 it increased to 0.42, indicating sparse vegetation cover. Over the following years, NDVI values demonstrated consistent growth, reaching 0.63 in 2015 and 0.82 in 2024, suggesting successful natural forest regeneration (Fig. 7A–E).

By 2024, in the burned area of sample plot №3, which was impacted by a surface fire, a multi-aged Scots pine forest with a high regeneration density had developed. The height of pine trees reached 8–12 m, with trunk diameters of 15–25 cm. The regeneration density in this area was significantly higher than in plots affected by crown fires, ranging from 8,000 to 12,000 trees/ha.

The recovery process in this plot is notably faster compared to sample plot №4, where a crown fire had caused more severe disturbances to the ecosystem.

Sample plot №6 in Amankaragaj exhibits stable undergrowth and herbaceous vegetation, indicating favorable conditions for natural forest regeneration. The predominance of lingonberry and bilberry suggests moderately dry, acidic soils characteristic of pine forest ecosystems. Mosses and lichens play a vital role in maintaining plot humidity and regulating the microclimate (Table 7; Fig. 8).

Table 7. Composition and characteristics of tree species in sample plot №6.

Tree species	Height (m)	Diameter (cm)	Percentage composition (%)
Scots pine (*Pinus sylvestris*)	6.5 ± 1.2	12.3 ± 2.5	82%
Silver birch (*Betula pendula*)	9.2 ± 1.5	15.1 ± 3.0	10%
Aspen (*Populus tremula*)	12.8 ± 2.1	18.6 ± 4.2	5%
Willow (*Salix spp.*)	4.1 ± 0.8	6.4 ± 1.2	3%

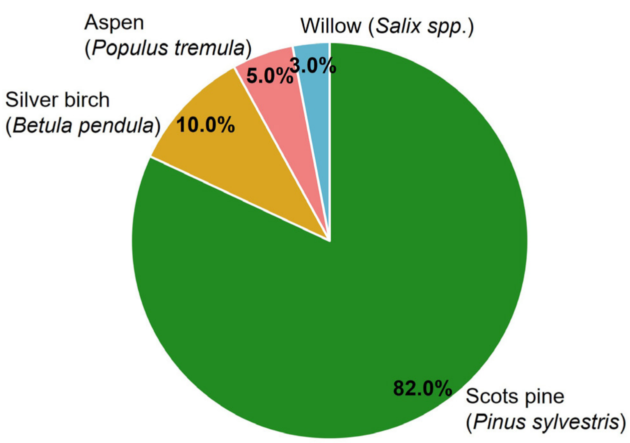

Figure 8. Tree species composition on sample plot №6.

Scots pine (*Pinus sylvestris*) constitutes the dominant component of the stand, indicating the establishment of a stable coniferous forest. The high proportion of this species is characteristic of resilient ecosystems. Silver birch (*Betula pendula*) is present to a considerably lesser extent compared to Scots pine. The low proportion of aspen (*Populus tremula*) may suggest that environmental conditions are not favorable for its active spread or that the ecosystem is undergoing stabilization, with coniferous species becoming dominant. Willow (*Salix spp*.) represents the smallest share among the tree species, confirming its localized distribution. This species is typically found in floodplain environments and wet areas, indicating the possible presence of depressions or moisture-rich zones within the study plot. Pine regeneration on the sample plot consists of trees of various age groups established through natural seed dispersal (Table 8).

Table 8. Development stages, age, height, diameter, and density of tree stands on sample plot №6.

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 ± 0.1	<1	3.8 ± 0.6
Saplings	6–10	1.4 ± 0.5	2.8 ± 1.2	2.5 ± 0.4
Young stand	11–20	5.3 ± 1.8	9.6 ± 3.1	1.7 ± 0.3

On the sample plot №6, several ecological factors affect the condition of the sapling stand. Major damage is caused by pests such as the pine moth (*Dendrolimus pini*), which induces defoliation (feeding on needles) and weakens young trees, as well as bark beetles (*Ips spp.*) that infest weakened trees, leading to their desiccation. Wild animals also contribute to damage by injuring the bark and young shoots, which impede sapling growth and may result in localized tree mortality. Climatic factors such as drought and wind stress further exacerbate the negative effects. Despite these natural stressors, the sapling stand in the sample plot maintains a satisfactory condition and continues its natural regeneration process.

The overall sapling density of Scots pine on this plot is 7–8 thousand individuals/ha, and silver birch (*Betula pendula*) is 3.0–3.5 thousand individuals/ha, though the density varies depending on plot-specific conditions. The sample plot exhibits a heterogeneous sapling composition, predominantly composed of both coniferous and deciduous species, with Scots pine being dominant due to the high shade tolerance of its young seedlings.

In the sample plot №6, a healthy sapling stand has been identified, indicating stable natural regeneration processes and the resilience of the forest stand. Despite competition for light and moisture from the mature forest, the sapling stand has successfully formed and is developing within normal parameters, confirming the ecosystem's self-sustaining capacity.

From 2004 to 2024, the NDVI values on the sample plot of plot №3 have consistently remained high (0.65–1.0) (Fig. 7A–E), attributable to the dense forest stand (pine, birch, aspen) and well-developed herbaceous and shrub layers. NDVI on the sample plots remains stable and significantly higher than on the burn areas of sample plots №4 and №6, even 20 years after the fire (Table 9; Fig. 9).

Table 9. Comparison of NDVI Dynamics on sample plots №3, 4, and 6.

Year	Sample plot №4	Sample plot №3	Sample plot № 6 (control)
2003	NDVI = 0.71–0.90 (high biomass)	NDVI = 0.59–0.71 (high biomass)	NDVI = 0.65–0.90 (stable condition)
2005	NDVI = 0.35–0.53 (significant decrease in photosynthetic activity)	NDVI = 0.40–0.60 (moderate decrease)	NDVI = 0.53–0.75 (minor changes)
2010	NDVI = 0.32–0.53 (active regrowth of grasses and shrubs)	NDVI = 0.32–0.53 (recovery of understory and herbaceous cover)	NDVI = 0.53–0.86 (stable forest development)
2015	NDVI = 0.63–0.80 (sapling development, beginning of forest formation)	NDVI = 0.60–0.80 (restored herbaceous cover and shrubs)	NDVI = 0.63–0.80 (mature forest)
2024	NDVI = 0.43–0.80 (near complete recovery)	NDVI = 0.59–0.90 (restored forest)	NDVI = 0.59–0.90 (natural state)

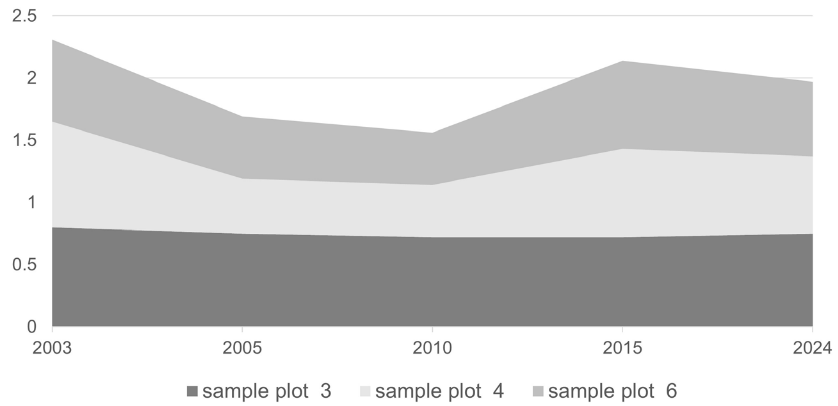

Figure 9. NDVI values from 2003 to 2024 on sample plots №6, №3, and №4 in the Amankaragay Forest Massif.

The dynamics of the NDVI index on sample plots №3, 4, and 6 reflect different stages of forest ecosystem recovery after the impact of fire and natural ecological factors.

Sample plot №6: On this plot, stable and high NDVI dynamics have been observed from 2004 to 2024, with values ranging from 0.6 to 0.8. These values confirm the presence of dense forest cover, including pine, birch, and aspen, along with a well-developed herbaceous and shrub layer. High NDVI values indicate stable vegetation recovery and the ecosystem's capacity for self-maintenance, despite competition from the mature forest for light and moisture.

Sample plot №4: On this plot, a lower NDVI trend has been observed, which is associated with the consequences of the fire that significantly altered the vegetation structure. In the early years after the fire, NDVI remained low, but over time, vegetation recovery took place. However, the NDVI value on this plot remains lower than on sample plots №3 and 6, which may indicate a slower recovery process, particularly due to more intense post-fire impacts.

Sample plot №3: This plot also demonstrates a certain delay in recovery, with NDVI dynamics similar to sample plot №4. Although there has been an increase in NDVI since 2004, it remains lower than on more stable plots like sample plot №3. This could be due to more severe vegetation destruction, which required a longer recovery period, as well as specific climatic and soil factors that slow down the recovery process.

It is worth noting that on background sample plots, the soil gradually becomes depleted due to long-term nutrient consumption by the trees. After a fire, burn areas benefit from the enrichment of the soil with ash, which contains available forms of nitrogen, phosphorus, and potassium, promoting rapid plant growth. In older forests, a significant portion of precipitation is absorbed by mature trees and understory, and much of it evaporates through the dense canopy. In burn areas, during the first few years after the fire, the soil receives more moisture because there is no mature tree canopy actively absorbing the water.

In the shaded conditions of the background plot, shade-tolerant species (such as birch, aspen, and willow) thrive, whereas pine grows more slowly due to the lack of sunlight. In burn areas, light-loving species such as pine dominate, showing faster growth.

4. Discussion

The analysis of contemporary research confirms that the NDVI, NBR, and dNBR indices are essential tools for assessing wildfire impacts and monitoring vegetation recovery across diverse ecosystems. These indices enable an objective evaluation of vegetation damage and regeneration dynamics; however, their effectiveness is contingent on ecosystem type, fire intensity, and climatic conditions.

Tokareva et al. (2021) further established that differences in NDVI and NBR values between burned and unburned plots persist for up to 17 years post-fire. Their study also revealed a significant correlation between index dynamics and climatic factors such as air temperature and precipitation, underscoring the necessity of incorporating environmental variables into assessments of post-fire vegetation recovery.

Our research confirms the high informativeness of the NBR, dNBR, and NDVI indices in assessing long-term post-fire vegetation dynamics. Notably, dNBR proved particularly effective for monitoring long-term changes: 20 years after a fire, dNBR values in areas affected by surface fires had declined to near-background levels, whereas in crown fire-affected areas, the index remained elevated, reflecting persistent structural and compositional differences. NDVI data indicated that vegetation productivity in moderate- and low-intensity surface fire zones had nearly returned to baseline forest levels, whereas productivity remained significantly reduced in crown fire-affected areas, highlighting variations in biomass accumulation and forest stand recovery.

The stages of post-fire succession described by Ramensky et al. (1994) are consistent with our findings. In the initial years following a fire, pioneer plant communities establish in burned areas, progressing through a predictable sequence: an herbaceous stage (1–5 years), a shrub and young tree stage (up to 25 years), the formation of secondary small-leaved forests (40–60 years), and ultimately, the re-establishment of a mature coniferous forest (120–150 years) (Gamova et al. 2023).

Research indicates that crown fires significantly disrupt forest ecosystem structure, impeding natural regeneration. Buryak and Kalenskaya (2020) found that post-crown-fire forest productivity remains low for decades, with regeneration favoring birch and aspen over conifers. In contrast, moderate-intensity surface fires stimulate seed germination and improve soil structure, thereby facilitating natural regeneration. These patterns align with the findings of Turner et al. (2019), who analyzed post-fire succession in Yellowstone National Park and determined that crown fires lead to the complete replacement of pine stands by aspen-dominated communities, with coniferous recovery requiring 50–100 years. Similarly, Pausas and Keeley (2021) demonstrated that in Mediterranean and Californian ecosystems, crown fires drive shifts toward shrub-dominated landscapes, while surface fires promote conifer regeneration.

Remote sensing methods provide objective, large-scale insights into forest recovery following wildfires. In Russia, Shvetsov and Ponomarev (2020) employed NBR, dNBR, and NDVI indices to analyze post-fire forest dynamics in Siberia, revealing that crown fire-affected areas maintained low NDVI values (0.7–0.8) even two decades post-fire.

Thus, our findings corroborate global research on the critical influence of fire type and intensity on forest ecosystem recovery. Integrated analysis using satellite-derived indices (NBR, dNBR, NDVI) and field data demonstrates that moderate-intensity surface fires promote natural forest regeneration, whereas crown fires necessitate prolonged recovery periods. The combination of remote sensing and field-based approaches represents a key strategy for advancing forest ecosystem management and post-fire rehabilitation efforts.

5. Conclusion

Natural regeneration of forest ecosystems after wildfires is a complex and prolonged process influenced by multiple factors, including fire intensity and type, vegetation composition, soil conditions, and regional climatic characteristics. This study analyzed post-fire dynamics in the Amankaragay Massif using three sample plots that differed in fire impact and recovery conditions.

The analysis confirms that forest recovery in the Amankaragay Massif following the 2004 wildfire is ongoing, with variations in recovery rate and intensity depending on local conditions and the degree of stand damage. The findings indicate that the Amankaragay forest currently retains a high potential for natural regeneration, sufficient for optimizing successional processes. Remote sensing data and field studies not only provide an assessment of the current state of forest ecosystems but also enable predictions about their future development, which is crucial for decision-making in forestry and nature conservation.

Fire intensity and type determine the rate of forest recovery. Analysis of spectral indices (dNBR, NBR, NDVI) and field data indicates that the degree of vegetation damage directly influences recovery speed. Crown fires cause severe ecosystem damage, delaying natural regeneration due to the loss of a significant portion of the stand and alterations in microclimatic conditions. In contrast, areas affected by moderate-intensity surface fires retained a substantial portion of pine regeneration and demonstrated a faster recovery rate due to the preservation of the parent stand, the availability of a seed bank, and minimal soil disturbance. The background pine forest maintained a consistently high level of development with an almost unchanged structure. The area affected by the crown fire is recovering at the slowest rate, with a greater presence of deciduous species.

dNBR and NDVI indices confirm the effectiveness of remote sensing for monitoring post-fire forest recovery.

Natural tree regeneration occurs through self-seeding and the presence of surviving parent trees. In areas where mature stands were preserved, sapling density was higher, and their condition was better compared to areas that experienced complete stand loss.

Sapling density depends on ecological conditions. More humid and sheltered areas show a higher number of young trees, whereas dry, nutrient-poor soils exhibit slower regeneration rates.

Biotic and abiotic factors significantly influence post-fire forest development.

Remote sensing data and field assessments enable not only an evaluation of the current forest condition but also predictions of future development. This is critical for developing conservation strategies, mitigating wildfire impacts, and informing forestry management decisions.

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Additional information

Conflict of interest

No conflict of interest was declared.

Ethical statement

No ethical statement was reported.

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Author contributions

Conceptualization: AZ, ZO. Data curation: MU. Funding acquisition: ZO. Methodology: AZ, ZO. Project administration: AZ. Resources: PZ, ZM. Software: ZM. Supervision: AZ. Validation: MU, ZM. Visualization: PZ, MU. Writing - original draft: ZO, AZ. Writing - review and editing: PZ, ZM.

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Data availability

All of the data that support the findings of this study are available in the main text or Supplementary Information.