

APPLICABILITY OF NBR AND dNBR INDICES IN ASSESSMENT OF PYROGENIC TRANSFORMATION AND POST-FIRE FOREST REGENERATION: CASE STUDY OF SOUTHEASTERN SIBERIA CONIFEROUS FORESTS

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ABSTRACT. This study evaluated the reliability of the Normalised Burn Ratio (NBR) and its differenced variant (dNBR) for assessing burnt areas and post-fire forest recovery. The research was conducted in the pine forests of the Tunka Depression (Southwestern Cisbaikalia), focusing on areas affected by a 2010 wildfire. Field data consisted of annual geobotanical observations from 2014 to 2022, which documented plant community regeneration across varying degrees of fire severity. Remote sensing analysis utilised Landsat 7 imagery (30 m resolution) between 2009 and 2022. Approximately 500 cloud-free NBR values were extracted from the USGS Landsat 7 Level 2, Collection 2, Tier 1 dataset using the Google Earth Engine platform. We assessed the spatiotemporal dynamics of these indices alongside the geobotanical parameters. The results confirm the effectiveness of NBR and dNBR for mapping burnt areas and determining initial fire severity. For detecting recent burns, mid-growing season imagery was most informative. Regarding post-fire regeneration analysis, springtime dNBR data were most reliable, as the influence of herbaceous cover on the spectral signal is minimised compared to the peak growing season. However, field observations revealed that the recovery of NBR values to pre-2009 fire levels by 2021 does not indicate that plant communities have regenerated to a near-natural state. This trend of rapid NBR recovery underscores the limitation of using NBR/dNBR indices alone for assessing long-term regeneration prospects. In conclusion, the results of the synthesised analysis of geobotanical and geoinformation materials showed that while remote sensing data effectively corroborate landscape-forming processes in disturbed ecosystems, their utility in detailed regeneration studies requires calibration with field data. The findings contribute to refining the application of NBR/dNBR indices and highlight the necessity of integrated approaches for calibrating remote sensing data.

KEYWORDS: burnt area, geobotanical observations, regeneration, monitoring, spectral index NBR, dNBR

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INTRODUCTION

In the spring of 2010, a large wildfire, a periodically recurring phenomenon in Southeastern Siberia, affected a portion of the Tunkinskiy National Park (Republic of Buryatia, Russia). Between 2002 and 2016, fires burnt 14,705.96 hectares within the park, which is slightly more than 1% of its total area (Ivanyo et al. 2017). A further 2,126.28 hectares burnt between 2019 and 2023¹, representing approximately 0.2% of the park's territory and 0.3% of its forested area. Despite the relatively limited extent of these fires, they frequently affect unique natural

complexes. The loss of these complexes diminishes the landscape's distinctiveness. These complexes include pine forests with isolated larch and birch specimens, an understory of Daurian rhododendron, and a ground cover of green mosses and grasses. These serve as a reference standard for the mountain-basin light coniferous forests of the region. The 2010 wildfire burnt 233 hectares of forest within the Badary area. Subsequent monitoring through geobotanical surveys from 2014 to 2022 revealed that this event increased the differentiation of the mosaic, age-altitude heterogeneous structure of forest plant populations (Atutova 2022; Atutova 2023).

¹ About the forestry departments of the Republic of Buryatia (2024). IAS "Nature of Buryatia" [online]. Available at: <https://ias.burpriroda.ru/forest/lesnichestva.php?ID=150464> [Accessed 27 Dec. 2024].

Given the importance of wildfire risk, the potential to use geobotanical monitoring results for studying pyrogenic transformation and forest regeneration dynamics in remote areas prompted the consideration of additional analytical methods. Satellite data are highly informative for this purpose, and specialised processing methods can calculate indices to facilitate the remote detection of burnt areas, assess fire severity, and analyse regeneration prospects. For analysing post-fire landscape changes, the calculation and spatiotemporal analysis of spectral vegetation indices have proven particularly effective (Ba et al. 2022; Chu et al. 2016; Kibler et al. 2019; Pushkin et al. 2015; Rodionova et al. 2020; Tokareva et al. 2021; Xofis et al. 2022). While these geodata are generally reliable for determining the post-fire state of plant communities, such conclusions are often not validated with field observations (Cuevas-González et al. 2009; Ba et al. 2022; Hao et al. 2022; Storey et al. 2016; Bastos et al. 2011; Bratkov and Ataev 2017; Casady and Marsh 2010). This gap raises questions about the application of these methods in studies of pyrogenic transformation. The authors' previous research, which synthesised field and satellite data, demonstrated that as phytomass increases during forest regeneration, spectral indices could show inflated values inconsistent with the area's actual geobotanical characteristics (Atutova 2024). This highlights the need to identify additional natural factors to improve the reliability of remote sensing data. A commonly used approach for assessing burnt areas is the calculation of the Normalised Burn Ratio (NBR) spectral index. The NBR has a wide dynamic range for characterising fire damage and a long recovery interval to pre-fire values (Shvetsov and Ponomarev 2020). Correlations between NBR values and phytomass have confirmed its effectiveness for mapping burnt areas and monitoring forest regeneration dynamics (Vorobiev et al. 2012; Sidelnik et al. 2018; Hao et al. 2022; Khakim et al. 2024), including in Siberian regions (Rodionova et al. 2020; Tokareva et al. 2021; Soromotin

et al. 2022; Shvetsov and Ponomarev 2020; Rozhkov and Kondakov 2017; Ponomarev et al. 2022).

This study investigates the relationship between changes in the geobotanical parameters of post-wildfire plant communities in the Badary area and the dynamics of the NBR and its temporal difference (dNBR). By integrating remote sensing data with field observations from areas affected to varying degrees by a 2010 wildfire, we aim to evaluate the utility of these indices for assessing pyrogenic transformation and post-fire forest regeneration. Furthermore, considering the distinct seasonal ecosystem dynamics of Southeastern Siberia, we sought to identify the vegetation periods in which NBR values are most reliable.

MATERIALS AND METHODS

Study sites

This study was conducted in the Badary area, a sandy massif in Southwestern Cisbaikalia, located in the central Tunka depression. The massif forms a flat, rounded summit with elevations of 780–855 m, and its surface is characterised by ridges and hollows shaped by aeolian processes. The region has a sharply continental climate. Meteorological data from the Tunka station for the central depression show a mean annual temperature of +0.6°C, with mean monthly temperatures of −24.2°C in January and +18.7°C in July (Vasilenko and Voropay, 2015). The recorded absolute temperature range is from −40.1°C to +32.6°C. Annual precipitation is approximately 300–350 mm. The wind regime is dominated by western and northern winds, influenced by the depression's latitudinal position and the deeply incised river valleys descending from the slopes of the Tunka Goletz Range to the north. We examined two key sites within the pine forests of the Badary area that were transformed to varying degrees by a wildfire in May 2010 (Fig. 1).

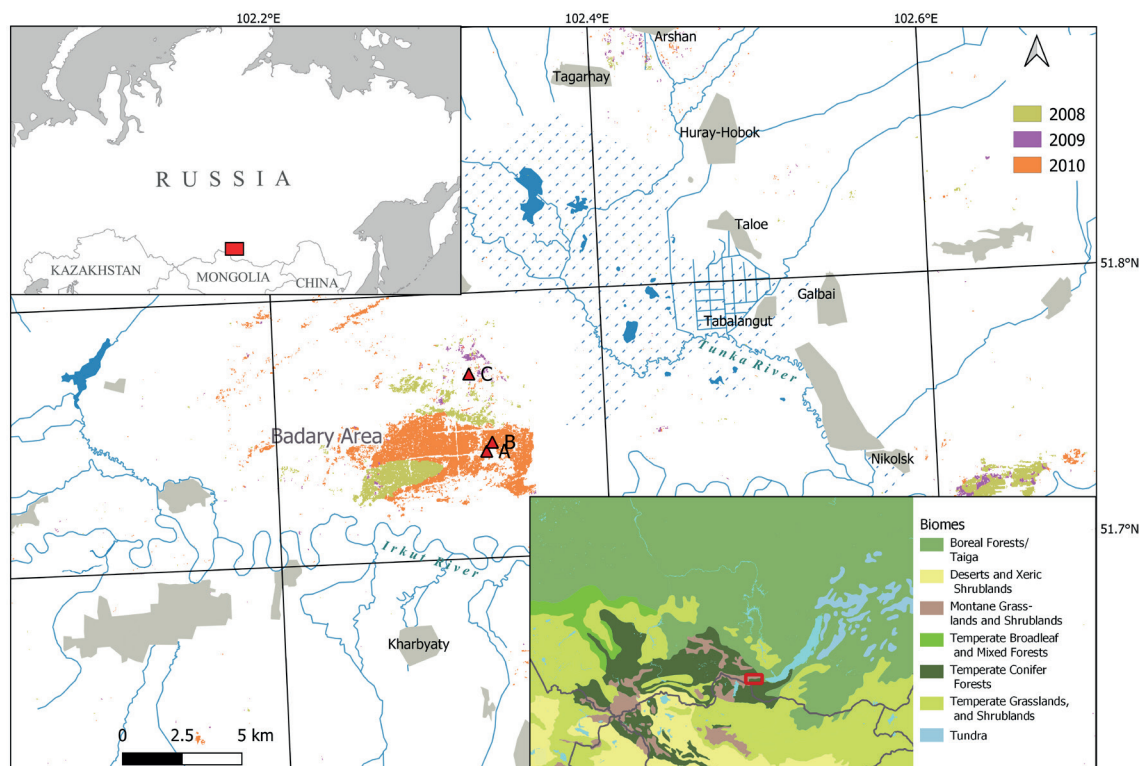


Fig. 1. Location of the study areas (A, B, C) within regional biomes² and historical fire perimeters³ (2008–2010)

² The ecoregion classifications for the study area were obtained from the Ecoregions geoportal www.ecoregions.appspot.com [Accessed 26 Sept. 2025].

³ Fire forest loss 2001–2022 [online]. Available at: https://glad.umd.edu/users/Alexandra/Fire_GFL_data/2001-22/ [Accessed 26 Sept. 2025].

Area A is a peripheral section of the burn scar, located 70 m from the forest edge. It experienced high-severity fire damage but retains some standing trees. Area B, situated 440 m from Area A and 250 m from the forest edge, is within the fire's interior. It experienced complete canopy consumption with no surviving trees. Due to negligible natural regeneration, this site was replanted with *Pinus sylvestris* seedlings by Tunkinskiy National Park staff in May 2016. Area C is an unburnt reference site on the eastern edge of the Badary area, 3.3 km from Site A and 3.0 km from B. It consists of a secondary, medium-aged (45–50 years) pine forest with occasional *Larix sibirica* and *Betula pendula*. It has an understory of *Rhododendron dauricum* and patches of moss-grass-shrub communities. This site was selected as a reference because there were no intact primary pine forests near the burnt area.

Geobotanical monitoring materials

Field observations began in 2014 at sites A and C, and in 2016 at site B after post-fire reforestation activities. Data were collected within 20 × 20 m permanent sample plots. The following parameters were recorded: tree undergrowth, including stand structure, species composition, average height, and species abundance

(using the Drude scale (1890)), and shrub layer and general plant communities, specifically species abundance (Drude scale), average height, and projective cover. The species composition of the tree undergrowth was quantified using a ten-unit formula based on relative abundance. Projective cover was estimated visually using a step-scale approach: a ten-step scale for the herbaceous layer, a five-step scale for the shrub layer, and a single-step scale for the overall plant community. These data were synthesised into regeneration sets, which characterise the post-fire recovery dynamics of plant communities under specific landscape-ecological conditions (Table 1).

Geoinformation materials

Landsat 7 satellite imagery (30 m resolution) was used as the primary data source, matching the spatial and temporal scale of the field observations. This dataset showed the highest consistency between the derived spectral indices and the multi-temporal field data. To identify burnt areas and analyse post-fire dynamics, we calculated the Normalised Burn Ratio (NBR) index. The NBR uses spectral reflectance in the near-infrared (NIR) and shortwave infrared (SWIR) regions, which are sensitive to vegetation chlorophyll content and moisture, respectively

Table 1. Post-fire regeneration dynamics in the Badary area (Southwestern Cisbaikalia)

Parameters	Site A					Site B							
	2014	2016	2018	2020	2022	2016	2018	2020	2022				
Site description													
Vegetation before wildfire	<i>Pinus sylvestris</i> with single specimens of <i>Larix sibirica</i> and <i>Betula pendula</i> with undergrowth of <i>Rhododendron dauricum</i> green-moss-herb-subshrub forest												
Pyrogenic features	Edge part (flank) of the ground fire					Aria of the main part of the ground fire							
Undergrowth													
Composition (formula ¹)	1P9B	2B8P	1B9P	1B9P	1B9P	2B8P	1B9P	1B9P	1B9P				
<i>Betula pendula</i>													
Average height, m	0.9	1.2	1.6	1.8	2.0	0.8	1.1	1.2	1.3				
Projective cover, %	5	5	5	5	5	3	5	5	5				
<i>Pinus sylvestris</i>													
Natural (✓) and artificial reproduction (✱)	✓	✓	✓	✓	✓	✓	✱	✓	✱	✓	✱	✓	✱
Average height, m	0.06–0.1	0.25–0.3	0.7	1.5	2.0	0.3	0.08	0.7	0.2	1.3	0.4	1.8	0.6
Projective coverage, %	5	30	50	60	70	15	5	30	5	30	5	40	5
<i>Shrub layer</i>													
Average height, m	0.20	0.25	0.40	0.40	0.6	0.3	0.5	0.7	0.7	0.7	0.7	0.7	0.7
Projective coverage, %	15	20	25	30	35	30	30–35	40	40	40	40	40	40
Drude abundance of dominant species ²													
<i>Rosa acicularis</i>	<i>sp.</i>	<i>sp.</i>	<i>sp.</i>	<i>sp.</i>	<i>sp.</i>	<i>cop.</i> ¹	<i>cop.</i> ¹	<i>cop.</i> ¹	<i>cop.</i> ¹	<i>cop.</i> ¹	<i>cop.</i> ¹	<i>cop.</i> ¹	<i>cop.</i> ¹
<i>Rhododendron dauricum</i>	<i>sol.</i>	<i>sol.</i>	<i>sp.</i>	<i>sp.</i>	<i>sp.</i>	-	<i>sol.</i>	<i>sol.</i>	<i>sol.</i>	<i>sol.</i>	<i>sol.</i>	<i>sol.</i>	<i>sol.</i>
<i>Herb layer</i>													
Average height, m	0.3	0.5	0.5	0.5	0.7	0.4	0.5	0.6	0.7	0.7	0.7	0.7	0.7
Projective coverage, %	40	50	60	70	80	60	70	80	80	80	80	80	80

Drude abundance of dominant species ²									
<i>Calamagrostis Langsdorffii</i>	<i>cop.</i> ²	<i>cop.</i> ³	<i>cop.</i> ³	<i>cop.</i> ³	<i>cop.</i> ³	<i>cop.</i> ²	<i>cop.</i> ²	<i>cop.</i> ²	<i>cop.</i> ²
<i>Carex duriuscula</i>	-	<i>sp.</i>	<i>cop.</i> ¹	<i>cop.</i> ¹	<i>cop.</i> ¹	<i>sp.</i>	<i>cop.</i> ¹	<i>cop.</i> ¹	<i>cop.</i> ¹
<i>Chamerion angustifolium</i>	<i>cop.</i> ²	<i>cop.</i> ²	<i>cop.</i> ¹	<i>sp.</i>	<i>sol.</i>	<i>cop.</i> ²	<i>cop.</i> ²	<i>cop.</i> ¹	<i>cop.</i> ¹
<i>Artemisia sericea</i>	<i>sp.</i>	<i>cop.</i> ²	<i>cop.</i> ²	<i>cop.</i> ²	<i>cop.</i> ²	<i>sp.</i>	<i>sp.</i>	<i>cop.</i> ¹	<i>cop.</i> ¹
<i>Geranium pratense</i>	<i>cop.</i> ¹	<i>cop.</i> ²	<i>cop.</i> ²	<i>cop.</i> ²	<i>cop.</i> ²	<i>cop.</i> ²	<i>cop.</i> ²	<i>cop.</i> ²	<i>cop.</i> ²
<i>Sanguisorba officinalis</i>	<i>cop.</i> ¹	<i>cop.</i> ¹	<i>cop.</i> ¹	<i>cop.</i> ¹	<i>cop.</i> ¹	<i>cop.</i> ¹	<i>cop.</i> ¹	<i>cop.</i> ²	<i>cop.</i> ²
<i>Trifolium medium</i>	<i>sp.</i>	<i>cop.</i> ²	<i>cop.</i> ²	<i>cop.</i> ²	<i>cop.</i> ²	<i>cop.</i> ¹	<i>cop.</i> ¹	<i>cop.</i> ²	<i>cop.</i> ²
<i>Vicia cracca</i>	<i>sp.</i>	<i>cop.</i> ¹	<i>cop.</i> ¹	<i>cop.</i> ¹	<i>cop.</i> ¹	<i>sp.</i>	<i>sp.</i>	<i>sol.</i>	<i>sol.</i>
<i>Rubus saxatilis</i>	<i>sol.</i>	<i>sp.</i>	<i>cop.</i> ¹	<i>cop.</i> ¹	<i>cop.</i> ¹	<i>sp.</i>	<i>sp.</i>	<i>cop.</i> ¹	<i>cop.</i> ¹
<i>Vaccinium vitis-idaea</i>	<i>sol.</i>	<i>sp.</i>	<i>cop.</i> ¹	<i>cop.</i> ¹	<i>cop.</i> ¹	-	<i>sol.</i>	<i>sp.</i>	<i>sp.</i>
<i>Pleurozium schreberi</i>	-	-	<i>sol.</i>	<i>sp.</i>	<i>sp.</i>	-	<i>sol.</i>	<i>sol.</i>	<i>sol.</i>

Note: ¹ – B – *Betula pendula*; P – *Pinus sylvestris*; ² – Drude abundance for dominant species: *cop.*³ – plants are very abundant; *cop.*² – there are many individuals; *cop.*¹ – there are quite many individuals; *sp.* – plants are found in a small number, scattered; *sol.* – plants are found in a very small number, a few specimens

(Bartalev et al. 2010; Rodionova et al. 2020; Tokareva et al. 2021; Sidelnik et al. 2018; Hao et al. 2022; Kharitonova and Kharitonova 2021) (Table 2). The index is calculated in the Appendices (Table A). The near-infrared band characterises changes in the chlorophyll content of drying vegetation; the mid-infrared band determines the moisture content (Rodionova et al. 2020). All processing was conducted on the Google Earth Engine platform using a custom JavaScript code. The code specified the data source (USGS Landsat 7 Level 2, Collection 2, Tier 1 surface reflectance), applied a cloud mask, defined the study area coordinates and period (2009–2022), and executed the NBR calculation to extract time series values for each sample point. Calculations were based on the brightness values of pixels containing the central points of each sample plot. The resulting NBR values range from –1 to +1, where higher values (closer to +1) indicate healthy vegetation, and lower values (closer to 0 and below) indicate fire-damaged areas (Vorobiev et al. 2012; Hao et al. 2022). Approximately 200 NBR values were initially generated for each observation point from the pre-fire year (2009) to 2022, equating to roughly 14 observations per year. However, about 40% of these values were excluded due to cloud cover and data gaps from the Scan Line Corrector failure on the Landsat 7 ETM+ instrument. This is consistent with the satellite's 16-day revisit cycle, which provides a theoretical maximum of 22 images per year.

Geobotanical observations confirmed that vegetation cover is the most dynamic and rapidly recovering ecosystem component. In the initial stages of post-fire succession

(demutation), the abundance and average height of herbaceous vegetation significantly exceeded those of tree seedlings (Atutova, 2022). Given the strong seasonal dependence of geobotanical characteristics, which is reflected in spectral data (Hao et al., 2022; Radjabova et al., 2020; Avetisyan et al., 2022), we defined three distinct growing seasons relevant to landscape development in a continental climate. For each year from 2009 to 2022, we selected NBR values from the following periods: 15 April – 15 June; 16 June – 15 August; and 16 August – 15 October. Values corresponding to the exact dates of in situ observations (2014–2022) were also extracted, resulting in a total of 492 NBR values from cloud-free periods.

At the next stage, the average NBR indicator was determined for each site in each vegetation phase for each year (from 2009 to 2022). This was calculated by summing all values for a set and dividing by their number. These means were derived from two to five cloud-free observations per season. We also established a seasonal background value for the unburnt area (Area C). This was defined as the arithmetic mean of all seasonal average values from 2009 to 2022. Comparing NBR indices on burnt areas against these background values allows for an assessment of satellite data reliability in determining pyrogenic transformation.

To quantify fire-induced environmental damage, we employed the differenced Normalised Burn Ratio (dNBR). This is calculated as the pre-fire NBR minus the post-fire NBR (Miller and Thode 2007; Bartalev et al. 2010; Vorobiev et al. 2012; Hao et al. 2022) (Table 2). To track recovery

Table 2. Selected spectral indices used in remote assessment of burnt areas in pine forests of the Badary area

Index	Expression	Description
Normalised Burn Ratio (NBR)	$(\text{NIR} - \text{SWIR}) / (\text{NIR} + \text{SWIR})$	Detects the burnt areas
the differenced Normalised Burn Ratio (dNBR)	NBRprefire data – NBRpostfire data	Evaluates the degree of pyrogenic transformation after ignition
dNBRseverity (dNBRs)	NBRprefire data – NBRregrowth data	Reflects the change in the degree of pyrogenic transformation during the regeneration process
dNBRregrowth (dNBRr)	NBRpostfire data – NBRregrowth data	Reflects the dynamics of regrowth during the regeneration process

dynamics, we used two variants. The dNBRs represents the difference between the pre-fire NBR and the NBR for each subsequent year, indicating changes since the fire. The dNBRr represents the difference between the immediate post-fire NBR and each subsequent year, indicating annual recovery progress (Santos et al. 2020). Applying these formulas produced a geodataset structured by vegetation season, facilitating remote assessment of forest restoration (Table A). Positive dNBRs and dNBRr values indicate a decrease in vegetation, while negative values signify an increase. The parallel trajectories of dNBRs and dNBRr (Fig. 2) confirm that dNBRs is informative not only for assessing initial fire damage but also for monitoring early-stage vegetation recovery.

Synthesizing the calculated indices with field data will enable the classification of geodata by the degree of pyrogenic transformation in the region's light-coniferous forests. A preliminary review of dNBR threshold values for similar landscapes in Southeastern Siberia (Bartalev et al. 2010; Tokareva et al. 2021; Ponomarev et al. 2022) and adjacent territories (Hao et al. 2022) revealed significant variability in published ranges for determining burn severity. Therefore, to rank dNBR values according to wildfire damage degree, we employed a field-data generalisation method based on R.V. Chugunova's (1960) classification of

burnt areas. At the start of observations, site A corresponded to a burnt area with complete stand mortality, while site B was a damaged stand represented by a treeless space with charred trunks. The analysis of post-fire regeneration was based on correlating dNBRr indices with the geobotanical specifics of each successional stage defined by Chugunova (1960): blackened burnt forest, grass stage, grass-shrub stage, and coniferous young growth.

RESULTS

A smooth, non-fluctuating NBR value trend was observed, particularly during the mid-growing season, in the background (unburnt) area (Fig. 2, Table A). The high canopy density here suppresses light-demanding pine undergrowth, and the living ground cover is sparse due to the inhibitory effect of the coniferous litter. Monitoring at this site revealed that the projective cover of the herbaceous layer influences the differentiation of NBR values across seasons. As the projective cover increased from 30% in spring to 70% at the peak of vegetation, the NBR values rose by almost 25% (Fig. 3). Overall, the mean NBR values for the background area were 0.545 at the beginning of the growing season, 0.586 in the middle, and 0.648 at the end.

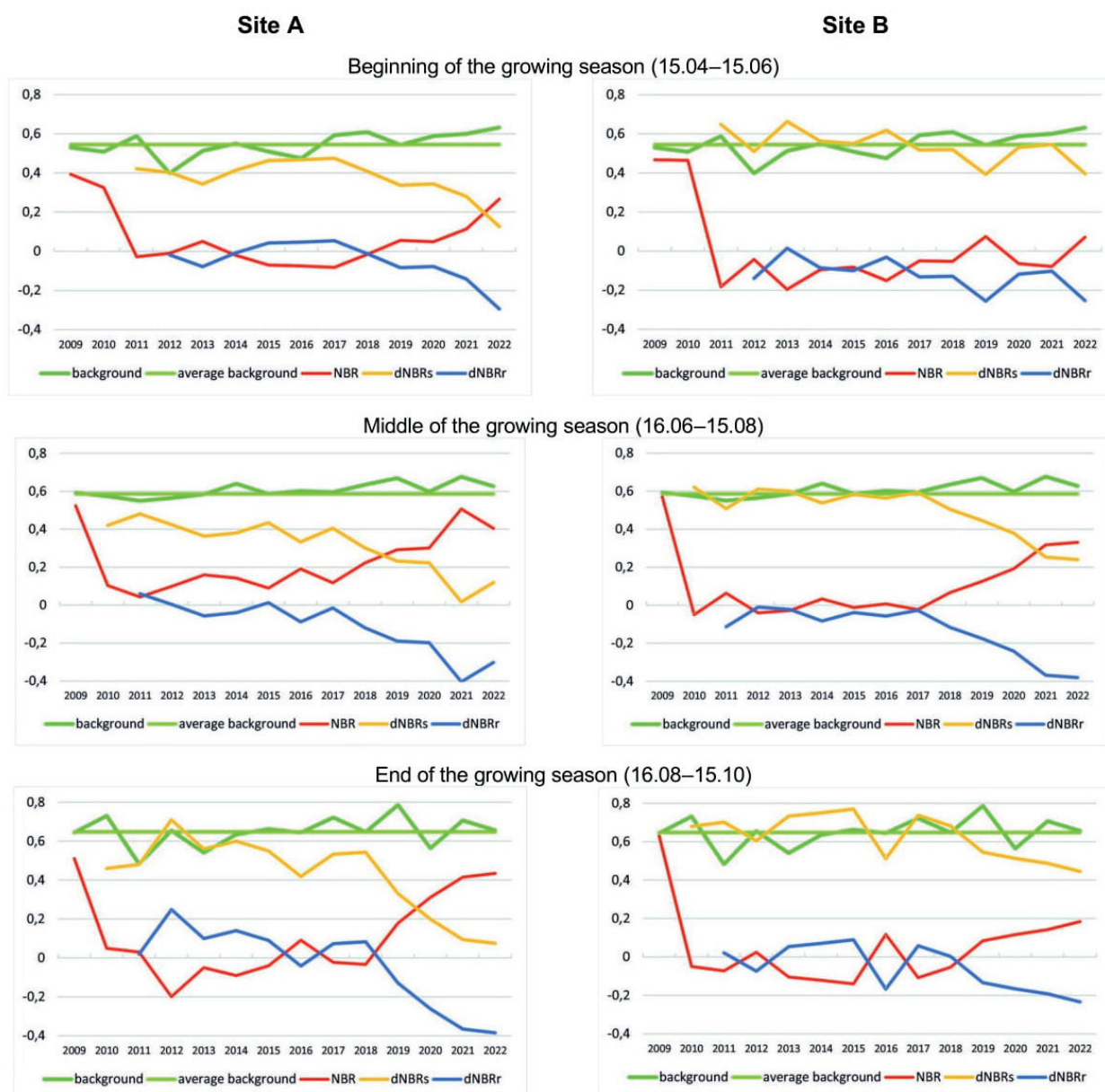


Fig. 2. Dynamics of NBR, dNBRs and dNBRr during post-fire forest regeneration in the Badary area

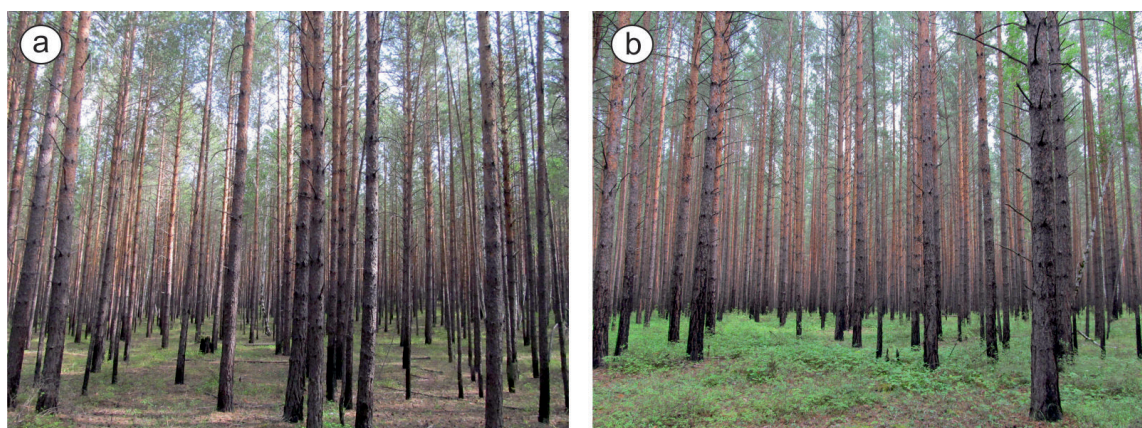


Fig. 3. Variation in NBR with seasonal changes in herbaceous projective cover at the reference site (site C). Panel (a): early growing season (5 June 2014) showing moderate cover and an NBR of 0.550. Panel (b): peak growing season (8 July 2021) showing high cover and an NBR of 0.677

Analysis of the remote sensing data revealed a clear differentiation in NBR values between the two areas affected to different degrees by the 2010 wildfire. Prior to the fire (mid-growing season 2009), both sites exhibited high NBR values (site A: 0.524; site B: 0.571). Following the fire in 2010, these values plummeted to 0.103 and -0.050 , respectively. This sharp decline, corresponding to dNBRs values of 0.421 for site A and 0.621 for site B, confirmed a high severity burn across both areas.

The spectral difference between the sites persisted in the initial post-fire years (Table A). Site B consistently showed lower NBR values than site A. This can be attributed to two factors: the storage of fallen timber at site B and subsequent damage to the living ground cover from machinery during furrowing for replanting in 2016. In contrast, site A, which retained some standing trees and offered better conditions for grass cover development, showed a stronger spectral signal of early regrowth (Fig. 4). From the fire year until 2018, mid-season NBR values at site A ranged from 0.043 to 0.222, while at site B they varied from -0.050 to 0.660 (Table A). Despite this increase, field observations confirmed that both sites remained significantly transformed. The dNBRs values for this period remained high (site A: 0.302–0.481; site B: 0.505–0.621), indicating a persistent spectral signature of fire damage relative to the pre-fire baseline. However, the differential recovery rates were captured by the dNBRr. At site A, dNBRr values decreased from 0.060 to -0.119 between 2011 and 2018, reflecting rapid vegetation regeneration (Table 1). In contrast, the decrease at site B was negligible (from -0.113 to -0.116), aligning with its slower recovery due to the aforementioned disturbances (Fig. 4).

A marked increase in NBR values coincided with the growth of tree undergrowth and grass cover. At site A, NBR values rose to 0.507 in 2021 and 0.405 in 2022. Field data confirmed intensive regeneration, with pine undergrowth height increasing from 0.1 m in 2014 to 2.0 m in 2022, and its projective cover reaching 70% (Fig. 4). Concurrently, the herbaceous layer reached 80% projective cover and 70 cm in height. This successful recovery is further evidenced by the trends in difference indices. The dNBRs values declined from 0.232 to 0.017 between 2019 and 2022, signalling a spectral convergence with the pre-fire state. Simultaneously, the dNBRr values fell from -0.189 to -0.404 , underscoring strong positive vegetation growth relative to the immediate post-fire condition.

At site B, mid-growing season NBR values showed a consistent positive trend, increasing from 0.292 in 2019 to 0.405 in 2022 (Table 2). This recovery was driven by natural regeneration. The height of natural pine seedlings

increased from 0.3 m to 1.8 m and their projective cover from 15% to 40% over the same period (Fig. 4). In contrast, the planted *Pinus sylvestris* seedlings showed slow growth, reaching only 0.6 m in height with 5% projective cover by 2022. The strong herbaceous layer (80% cover, 70 cm height) contributed significantly to the spectral signal. The declining dNBRs (from 0.446 to 0.240) and dNBRr (from -0.175 to -0.381) values confirm a strong, positive vegetation recovery trend.

Analysis of NBR data for the beginning and end of the growing season, specifically during the initial stages of grass cover emergence and its subsequent wilting phase, between 2010 and 2018 also revealed a differentiation of burnt areas by the degree of pyrogenic transformation. In some years, the more severely damaged site B exhibited higher NBR values than the less damaged site A (Table A). It is noteworthy that at site A, positive late-season NBR values in 2010–2011 later turned negative, potentially reflecting the gradual fall and decomposition of dead standing timber. This initially provided a structural signal that was later lost. The dNBRs and dNBRr values in 2010–2018 were high, reaching 0.709 and 0.249, respectively, at site A in 2012, and 0.769 and 0.090, respectively, at site B in 2015.

The spectral difference between sites affected by different burn severities was most pronounced in the final observation stage (Table A). Starting in 2019, the dNBRs values at the beginning of the growing season at site A decreased from 0.344 to 0.127, and at site B from 0.531 to 0.396. By the end of the growing season, the values decreased from 0.331 to 0.075 and from 0.545 to 0.445, respectively. For the same period, the dNBRr values at the beginning of the growing season decreased from -0.084 to -0.294 at site A and from -0.103 to -0.253 at site B. At the end of the growing season, the dNBRr at site A decreased from 0.331 to 0.075, while at site B it decreased from -0.134 to -0.234 . These trends indicate that the spectral properties of the pyrogenically transformed areas became more consistent with the natural environment at both the beginning and end of the growing season. However, the extended autumn senescence period leads to elevated NBR values (Table A). Consequently, the NBR values from the beginning of the growing season correlate most reliably with the field observation data.

This study confirms the utility of satellite data for identifying burnt areas, assessing burn severity, and monitoring post-fire forest regeneration dynamics. However, in the sharply continental climate of Southern Eastern Siberia, where seasonal variability is pronounced, the timing of image acquisition is critical. The rapid recovery of grass cover disproportionately influences spectral

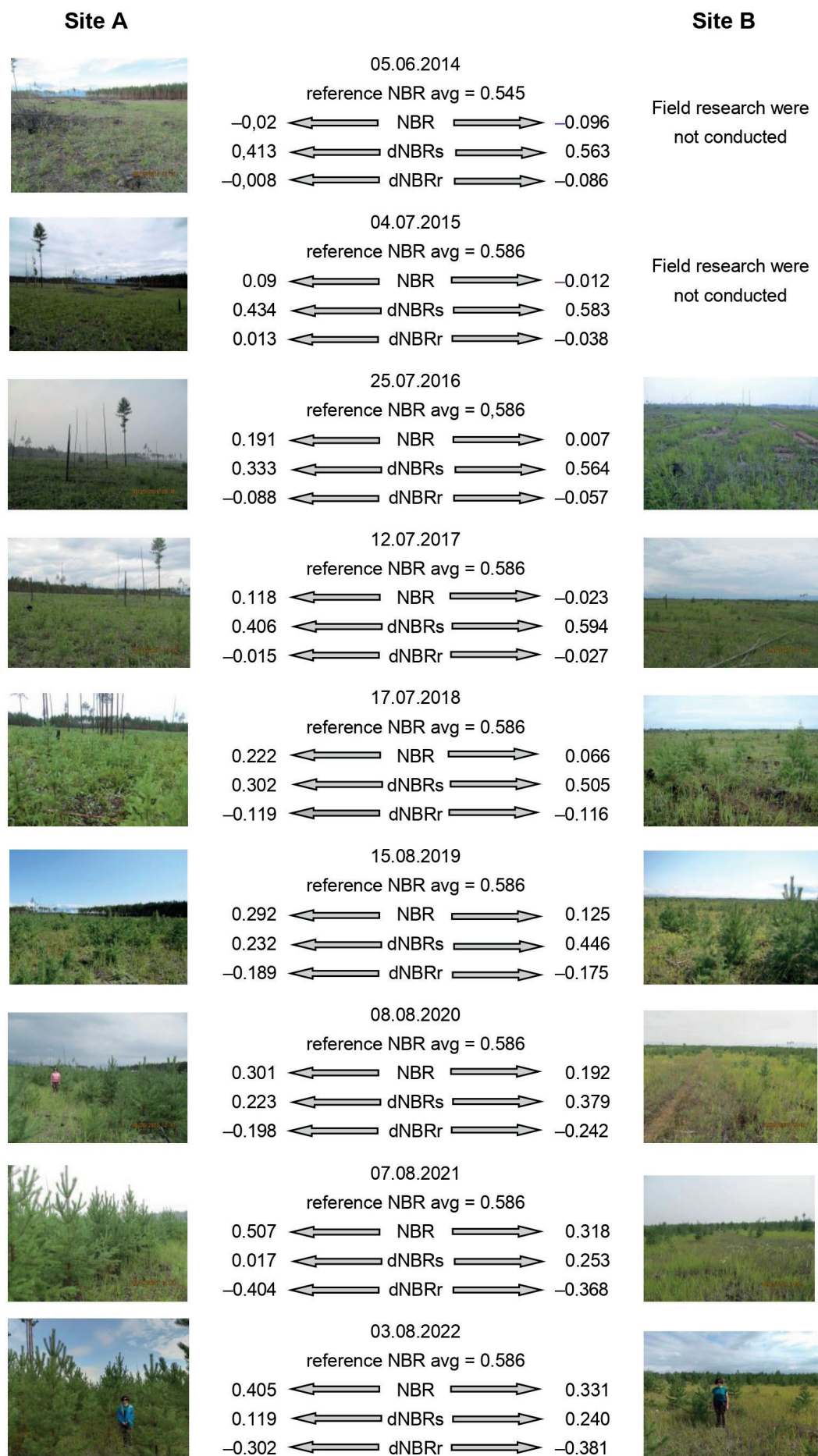


Fig. 4. Multi-temporal NBR and dNBR values for burnt areas in the Badary area (Tunka depression, Southwestern Cisbaikalia), with corresponding field photographs

indices, often leading to an overestimation of recovery. Consequently, for assessing post-fire ecosystem dynamics in similar landscapes, we recommend prioritising spring imagery, when herbaceous abundance and projective cover are minimal, to most accurately evaluate the recovery of woody vegetation.

DISCUSSION

This study aimed to evaluate the reliability of satellite data for assessing pyrogenic transformation and post-fire regeneration in the pine forests of Southern Eastern Siberia. A comparison of NBR and dNBR index values with the geobotanical characteristics of recovering plant communities in the Badary burnt area indicated the validity of these indices for identifying fire-affected areas and determining burn severity, consistent with previous findings (Rodionova et al. 2020; Avetisyan et al. 2022). Furthermore, our results prove the informativeness of dNBRs and dNBRr dynamics for monitoring post-fire forest regeneration (Santos et al. 2020).

It is known that the NBR index is calculated from the spectral brightness of pixels in the near-infrared region of the spectrum (Sidelnik et al. 2018; Tokareva et al. 2021). This region is associated with high photosynthetic activity. In the sharply continental climate of Southern Eastern Siberia, this relationship is evident in strong seasonal variations of the index, with the highest values consistently occurring during the mid-growing season. Analysis of the background area from 2009 to 2022 revealed the smallest inter-annual variability in NBR during this peak vegetation period, indicating stable ecological conditions in unburnt forests. Therefore, the long-term stability of high mid-season NBR values can serve as a reliable spectral marker for identifying areas unaffected by wildfire.

Our results confirm the utility of the dNBR index for delineating burnt area boundaries, consistent with previous studies (Miller and Thode 2007; Santos et al. 2020; Delcourt et al. 2021; Khakim et al. 2024; Ponomarev et al. 2022). The differentiation of dNBRs values between sites in the initial post-fire years correlated strongly with their observed burn severity. This indicates the reliability of remote sensing data in determining the extent of fire damage. In the fire year, the more severely impacted site B – classified as a treeless open space (Chugunova 1960) – exhibited dNBRs values of 0.621–0.679. In contrast, the less damaged site A, characterised by deadwood and fallen trees (according to Chugunova's classification (1960)), showed lower values of 0.421–0.460.

This clear differentiation enables the establishment of threshold dNBR values for ranking pyrogenic transformation. While studies in Siberia indicate that dNBR values >0.600 typify high-severity burns (Tokareva et al. 2021; Ponomarev et al. 2022), our research suggests that in the pine forests of Southeastern Siberia, values as low as 0.400 also indicate significant damage, a finding consistent with coniferous forests in northeastern China

geographically close to our areas (Hao et al. 2022). Based on our analysis, we propose the following severity classification for early-season data: dNBRs >0.500 indicates a high degree of pyrogenic transformation, while values of 0.400–0.500 indicate a moderately high degree (Table 3). Furthermore, this dNBRs gradation can be interpreted in terms of ecosystem recovery rates. High dNBRs values (>0.500), corresponding to dNBRr values above zero, indicate very low regeneration rates. Moderately high dNBRs values (0.400–0.500), corresponding to dNBRr values from -0.140 to zero, indicate low regeneration rates.

Until 2018, both sites showed ecological constraints that slowed the regeneration of woody vegetation, despite vigorous herbaceous recovery. This was reflected in persistently high dNBRs values, ranging from 0.302 to 0.709 at site A and from 0.393 to 0.769 at site B across different seasons. A shift towards stabilised ecological conditions and accelerated forest recovery began around 2019–2020, marked by increased growth rates of natural tree seedlings (Table 1). At site A, mid-growing season dNBRs values dropped below the 0.400 threshold (0.232 in 2019, 0.223 in 2020). However, considering the landscape context – a site with significant prior damage in the initial stage of young forest growth with a well-developed grass cover (according to Chugunova's classification (1960)) – the early-season dNBRs values of 0.337 and 0.344 for 2019–2020 were more ecologically informative. Consequently, we interpret early-season dNBRs values below 0.400 to indicate a moderate degree of pyrogenic transformation or average forest regeneration rates, corresponding to dNBRr values greater than -0.140 . In contrast, dNBRs values at site B during this period remained above the 0.400 threshold across all seasons. This aligned with field observations classifying the site at the grass-shrub stage of succession with successfully establishing woody undergrowth (according to Chugunova's classification (1960)), indicating that while recovery was underway, the spectral signature of the initial severe damage remained dominant.

In the final observation years (2021–2022), spectral indices indicated ongoing recovery. At site A, mid-growing season dNBRs values decreased to 0.017 and 0.119, while early-season values were 0.280 and 0.127. Despite continued growth in pine undergrowth height and cover, the overall landscape-ecological situation still indicated a moderate degree of pyrogenic transformation. At site B, mid-season dNBRs values also declined to 0.253 and 0.240, with early-season values falling to 0.546 and 0.396. Nevertheless, this site was still classified at a moderately high degree of fire damage. This status was corroborated by dNBRr values that remained within the range characteristic of areas with low forest regeneration rates. These final results suggest that the lower threshold of the dNBRs range for a 'moderate' transformation class has not yet been fully defined. Therefore, determining the precise lower limits of dNBRs that signify a transition to advanced recovery and average regeneration rates requires continued long-term monitoring.

Table 3. A Classification of pyrogenic transformation and forest regeneration rates in the pine forests of the Badary area

dNBRs index	Degree of pyrogenic transformation	Forest regeneration rates	Stages of overgrowth of burnt areas (Chugunova 1960)
dNBRs > 0.500	High degree	Very low rates	Black burnt area; grass stage
$0.400 < \text{dNBRs} < 0.500$	Moderately high degree	Low rates	Grass stage; grass-shrub stage
$?^1 < \text{dNBRs} < 0.400$	Moderate degree	Average rates	Grass-shrub stage; coniferous young stands

Note: ¹ – continued observations are required to determine the minimum dNBRs limit

Long-term dNBR data for the end of the growing season consistently showed elevated values throughout the 12-year post-fire period, especially in the later observation stages. In some years, late-season NBR and dNBRs values even exceeded those from the mid-growing season (Table A). As with the mid-season data, this increase is attributed to the influence of the rapidly recovering herbaceous layer. This finding highlights the importance of using early-growing-season imagery for the remote analysis of long-term post-fire restoration in evergreen light-coniferous forests. This is because this period is not affected by the confounding spectral influence of dense grass cover.

This study demonstrates the utility of synthesising satellite data with field observations for calibrating remote sensing indicators. We hypothesise that as undercanopy vegetation continues to develop over the coming years, NBR values may eventually stabilise at high, pre-fire levels. If this occurs, it would corroborate findings that the sensitivity of the NBR index diminishes as plant communities approach full recovery (Sidelnik et al., 2018). Our results confirm that spectral indices are most informative for assessing burn severity and initial recovery dynamics within the first decade following a fire.

Our study proves that the NBR and dNBR spectral indices are inadequate as primary tools for objectively assessing post-fire regeneration (demutation) (Soromotin et al. 2022; Avetisyan et al. 2022). Although NBR values increased progressively, exceeding pre-fire (2009) levels by the 11th year, field data show this does not signify a return to a natural ecosystem state. Instead, it highlights general trends in the demutation process. Therefore, assessments based exclusively on the NBR index are unreliable for evaluating reforestation prospects. These geospatial tools should be used as a supplementary (confirming) source to validate the development of landscape-forming processes.

CONCLUSIONS

This study proves that the NBR and dNBR spectral indices are effective tools for mapping burnt areas and evaluating pyrogenic transformation. We recorded a sharp decline in both indices following fire events, and the values effectively differentiated between zones of high and low fire severity. This pattern was consistent with field observations, confirming the utility of NBR and dNBR for ranking areas based on their level of fire impact.

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Through an integrated analysis of multi-temporal geospatial data and geobotanical monitoring, we identified key natural factors of forest regeneration that significantly influence the NBR spectral index. While the improvement in geobotanical characteristics of recovering undergrowth is a primary driver of the increasing NBR trend in burnt areas, our findings reveal that in early successional stages (demutation), the rapid re-establishment of grass cover is the dominant factor. This is evidenced by NBR data from a key study area that sustained less damage in the 2010 wildfire. Here, NBR values recovered to near pre-fire levels within eleven years, despite field observations confirming the landscape was still in an early stage of forest regeneration. Furthermore, we found that a sustained series of high NBR values with minimal mid-season fluctuation is a reliable indicator of areas approaching a natural state. Although data from the mid-vegetation period are useful for assessing early post-fire regeneration, our analysis shows that for light coniferous forests, NBR data from the early vegetation period are most advantageous. During this time, the confounding influence of living ground cover on index values is reduced compared to the peak growing season.

By analysing initial post-fire dNBR data and field observations, we established a threshold dNBR value of 0.500 to classify pyrogenic transformation in the Badary area's pine forests. Values above this threshold correspond to areas of high-severity burn (site B), while values below it indicate moderate-severity damage (site A). Given that these forests are in the early stages of post-fire regeneration, geobotanical data further allowed us to define threshold values for three rates of recovery: very low, low, and moderate.

The study revealed a tendency for NBR values to be overestimated, particularly in later demutation stages. This poses a significant risk to the reliability of remote forest recovery assessments. However, this discrepancy between satellite data and ground conditions does not prevent the integrated use of geospatial and geobotanical methods for evaluating landscape-forming processes. Extending the initiated observations will enable the development of additional criteria to enhance the utility of remote sensing data for studying forest regeneration in areas disturbed by fire. ■

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Appendices

Table A. Mean values of spectral indices for analyzing pyrogenic transformation and forest regeneration dynamics at key sites

Years	Site A			Site B			Site C	Average reference NBR values
	NBR	dNBRs	dNBRr	NBR	dNBRs	dNBRr	NBR	
Beginning of the growing season (15.04–15.06)								
2009	0.393			0.467			0.530	0.545
2010	0.326			0.464			0.508	– // –
2011	–0.028	0.421		–0.182	0.649		0.588	– // –
2012	–0.01	0.403	–0.018	–0.043	0.510	–0.139	0.398	– // –
2013	0.05	0.343	–0.078	–0.196	0.663	0.014	0.513	– // –
2014	–0.02	0.413	–0.008	–0.096	0.563	–0.086	0.55	– // –
2015	–0.07	0.463	0.042	–0.082	0.549	–0.10	0.509	– // –
2016	–0.075	0.468	0.047	–0.151	0.618	–0.031	0.475	– // –
2017	–0.082	0.475	0.054	–0.050	0.517	–0.132	0.593	– // –
2018	–0.015	0.408	–0.013	–0.053	0.520	–0.129	0.609	– // –
2019	0.056	0.337	–0.084	0.074	0.393	–0.256	0.643	– // –
2020	0.049	0.344	–0.077	–0.064	0.531	–0.118	0.588	– // –
2021	0.113	0.280	–0.141	–0.079	0.546	–0.103	0.600	– // –
2022	0.266	0.127	–0.294	0.071	0.396	–0.253	0.632	– // –
Middle of the growing season (16.06–15.08)								
2009	0.524			0.571			0.593	0.586
2010	0.103	0.421		–0.050	0.621		0.574	– // –
2011	0,043	0.481	0.060	0.063	0.508	–0.113	0.550	– // –
2012	0.100	0.424	0.003	–0.040	0.611	–0.010	0.565	– // –
2013	0.160	0.364	–0.057	–0.028	0.599	–0.022	0.585	– // –
2014	0.143	0.381	–0.040	0.033	0.538	–0.083	0.640	– // –
2015	0.090	0.434	0.013	–0.012	0.583	–0.038	0.586	– // –
2016	0.191	0.333	–0.088	0.007	0.564	–0.057	0.602	– // –
2017	0.118	0.406	–0.015	–0.023	0.594	–0.027	0.595	– // –
2018	0.222	0.302	–0.119	0.066	0.505	–0.116	0.635	– // –
2019	0.292	0.232	–0.189	0.125	0.446	–0.175	0.670	– // –
2020	0.301	0.223	–0.198	0.192	0.379	–0.242	0.598	– // –
2021	0.507	0.017	–0.404	0.318	0.253	–0.368	0.677	– // –
2022	0.405	0.119	–0.302	0.331	0.24	–0.381	0.627	– // –
End of the growing season (16.08–15.10)								
2009	0.510			0.629			0.644	0.648
2010	0,05	0.460		–0.050	0.679		0.731	– // –
2011	0.03	0.480	0.020	–0.076	0.701	0.022	0.483	– // –
2012	–0.199	0.709	0.249	0.024	0.605	–0.074	0.655	– // –

2013	-0.05	0.560	0.100	-0.104	0.733	0.054	0.541	- // -
2014	-0.09	0.600	0.140	-0.121	0.750	0.071	0.635	- // -
2015	-0.04	0.550	0.090	-0.140	0.769	0.090	0.662	- // -
2016	0.393	0.419	-0.041	0.314	0.512	-0.167	0.644	- // -
2017	-0.023	0.533	0.073	-0.108	0.737	0.058	0.712	- // -
2018	-0.033	0.543	0.083	-0.053	0.682	0.003	0.647	- // -
2019	0.179	0.331	-0.129	0.084	0.545	-0.134	0.786	- // -
2020	0.311	0.199	-0.261	0.116	0.513	-0.166	0.564	- // -