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Article

Dynamics of vegetation restoration on a sandy substrate in the northern taiga of Western Siberia (Numto Nature Park, Khanty-Mansi Autonomous Okrug – Yugra, Russia)

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Abstract. Restoring the vegetation in anthropogenically disturbed areas of northern Western Siberia is a pressing issue due to the large-scale development of oil and gas fields. Development of eroded sandy soil in the airport construction area near Numto settlement (Numto Nature Park, Western Siberia) is an example of manifestation of such disturbances. In 1993, 5.51 hectares of pine dwarf shrub-lichen forest on a sandy substrate were taken for the construction area. Since that time, the area experienced four stages of succession: (1) no vegetation, (2) moss, (3) dwarf shrub-moss, and (4) pine-dwarf shrub-moss-lichen. Thirty years after natural restoration has started, the share of the area without vegetation currently is less than 21%. Pioneer stage communities are formed by one species only, bog haircap moss *Polytrichum strictum.* At the next stage, dwarf shrubs (*Empetrum nigrum*) settle and sand hillocks are formed. More than 60% of the area is occupied by moss and dwarf shrub-moss communities. Vegetation develops most rapidly on the periphery of the area, where the tree layer of Scots pine *Pinus sylvestris* (4–8-m high) has formed, a lichen cover has appeared, and the community resembles the pristine one. According to the remote sensing spectral indicators, plant communities are gradually recovering in the disturbed area, amid a positive trend in surface air temperature and annual precipitation.

Keywords: anthropogenic transformation, remote sensing, overgrowing, succession, DI′, NDVI

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Научная статья

Динамика восстановления растительности на песчаном субстрате в северной тайге Западной Сибири (природный парк «Нумто», Ханты-Мансийский автономный округ – Югра)

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Аннотация. Восстановление растительного покрова на техногенно нарушенных территориях севера Западной Сибири является актуальной проблемой в связи с масштабным освоением месторождений углеводородного сырья. Представлены результаты исследований формирования растительности на площадке под строительство аэропорта у д. Нумто (природный парк «Нумто», Западная Сибирь), образовавшейся в 1993 г. на месте соснового кустарничкового-лишайникового леса на песчаном субстрате (площадь 5.51 га). Выделено 4 стадии зарастания: без растительности, моховая, кустарничково-моховая, сосново-кустарничково-мохово-лишайниковая. По прошествии 30 лет после образования площадки доля участков без растительности составляет менее 21%. Сообщества пионерной стадии образованы только одним видом мха *Polytrichum strictum*. Следующая стадия характеризуется поселением кустарничков (*Empetrum nigrum*) и формированием песчаных бугров. Более 60% площади занимают моховые и кустарничково-моховые сообщества. Наиболее быстро развивается растительность по периферии участка, где сформировался древесный ярус из *Pinus sylvestris* (от 4 до 8 м высотой), появился лишайниковый покров и сообщество приобрело вид, близкий к исходному. По данным спектральных индексов происходит постепенное восстановление растительных сообществ на нарушенном участке на фоне положительного тренда приземной температуры атмосферного воздуха и годовой суммы осадков.

Ключевые слова: антропогенная трансформация, дистанционное зондирование, зарастание, сукцессия, DI′, NDVI

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Introduction

Vegetation transformation and degradation is one of the major environmental issues associated with the large-scale development of hydrocarbon deposits in northern Western Siberia. Ecosystems with low resilience to anthropogenic (primarily mechanical) impacts, such as sparsely forested areas, northern taiga forests on sandy soils and raised bog complexes on permafrost, require special attention. However, to date the studies of vegetation succession under the influence of both climatic factors and anthropogenic disturbances are still scarce, in opposite to extensive observations of the permafrost state (Bobrik et al., 2015; Moskalenko, 1999). Widespread anthropogenic transformations, associated with oil and gas production, include active aeolian processes, occurring primarily on interfluve flat and gently rolling plains and terraces composed of fine and dusty sandy soils. In such areas, sand blowouts appear and expand, creating extremely unfavorable conditions for the vegetation formation and development. When lithological and landscape conditions are favorable enough, sand outcrops are formed even under weak anthropogenic loads (Soromotin and Sizov, 2007). Up to date, there is a number of studies devoted to the restoration of vegetation in disturbed areas in the northern taiga subzone, but primarily in sand quarries (Kapitonova et al., 2017; Koneva and Lashchinsky, 2014; Proskuryakova, 2002; Sizov, 2025; Sizov and Lobotrosova, 2016; etc.). Studying the nature and dynamics of vegetation restoration in such areas and planning effective reclamation measures, including the range of plant species used, remain relevant tasks.

The most comprehensive pattern of the plant communities and their restoration rate in disturbed areas can be obtained by combining traditional in situ monitoring methods with Earth remote sensing (ERS) data. The availability and volume of the latter have skyrocketed in recent decades. The increasing role of ERS methods in studying vegetation cover in general, and especially in hard-to-reach areas such as northern Western Siberia, is associated with the ability to access quickly the information about Earth surface objects. These data are obtained and provided by satellite systems with varying resolutions for vast territories over different time periods. Using ERS has several advantages comparing to traditional fieldwork, including much lower labor costs and obtaining additional environmental information for the study area (Duguay et al., 2005).

Methods of supervised classification of satellite images, analyzed together with vegetation indices, appear a very informative approach to assessing the dynamics of vegetation cover. This makes it possible to determine the spatial location of the boundaries of plant communities and to track their changes based on area characteristics and quantitative data on the degree of plant biomass development (Vorobyov et al., 2016). According to D.A. Kaverin et al. (2016), plant communities, growing on the soils with different geocryological conditions, are well differentiated using the Normalized Difference Vibration Index (NDVI) and the Disturbance Index (DI). Detecting the changes in forest cover based on subpixel differences in the spectral reflectance properties of the projective cover of the tree canopy is performed by multi-temporal imagery (Khovratovich et al., 2019), assessing forest restoration, by radar vegetation indices (Dual polarimetric Radar Vegetation Index, DpRVI) (Dmitriev et al., 2024), identifying the felling of individual trees based on shadows, by ultra-high-resolution satellite images (Aleksanin et al., 2019), etc. The wide variety of remote sensing methods for studying vegetation transformation allows to perform geobotanical observations and conclude on the influence of natural and anthropogenic destructive factors.

The area close to Numto settlement (Khanty-Mansi Autonomous Okrug – Yugra, Russia) was studied to assess the characteristics of vegetation restoration on sandy substrates. Construction of the airport near the settlement began in 1993 and was suspended after the site was cleared from the vegetation. Currently, this territory is located within the boundaries of the Numto Nature Park, established in 1997 to preserve the natural environment as a habitat and traditional activity of the indigenous peoples of the North. The central element of the park is Lake Numto, a relatively large body of water, sourcing the Nadym River; the lake has significant ecological, environmental, historical, and cultural significance (Valeeva et al., 2008).

Materials and methods

The construction site for the airport (N 63.504195° E 71.362985°) aimed for receiving and sending small aircrafts is located in the eastern part of the Beloyarsky District of the Khanty-Mansi Autonomous Okrug – Yugra, 1 km southeast of Numto settlement and the shore of Lake Numto, on the right bank of the Voshayegan River, in the northern taiga subzone (Fig. 1).

The study of the vegetation cover of the site was carried out on June 27, 2001 and August 31, 2024. In 2001, general geobotanical description was performed for the area of 1.5×200 m: these were the descriptions of 10 sites (20×50 cm), located every 2 m along the transect, oriented from north to south, sampling alternately on the left and right sides. The projective cover was assessed as a percentage in accordance to a 5-point Braun-Blanquet scale (Aleksandrova, 1969; Mirkin et al., 1989): r – the species is very rare, single specimens; + – <1%; 1 – 1–5%; 2 – 5–25%; 3 – 25–50%; 4 – 50–75%; 5 – >75%. Because of a large error in determining the geographic coordinates in 2001, it was not possible to subsequently establish the exact location of the transect. In 2024, five geobotanical descriptions were performed for a standard 100 m^2 area covering varying vegetation patterns along the western boundary of the site. A floristic survey of the entire site was also performed; two geobotanical profiles (AB and CD) were established in the northern part of the site at a 100 m distance from each other, crossing it from west to east (Fig. 2).

The nomenclature of vascular plant species is given according to the WFO Plant List (Elliott et al., 2025); bryophytes, according to N.G. Hodgetts et al. (2020); lichens, according to N.V. Sedelnikova (2017). Meteorological parameters (surface air temperature, annual and seasonal precipitation) for 1993–2024 are given according to the nearest Yuilsk weather station[1] (87 km WNW from the study area).

A map of the main plant communities was created based on the supervised classification of the WorldView-2 satellite image (spatial resolution of 2 m/pixel), related to the Esri World Imagery database, using ENVI 5.2 software package. The classification included several stages: (1) pre-processing of the satellite image, (2) developing training samples using field (in situ) data, (3) mapping using the Minimum Distance algorithm (MD), (4) assessing the level of confidence. Vectorization, area analysis, and map design were performed in QGIS 3.36.2[2].

[1] Weather and climate. Web page. URL: http://www.pogodaiklimat.ru/today/russia/khanty-mansiys-ao/yuilsk (accessed: 22.07.2025).

[2] QGIS. Web page. URL: https://qgis.org/ (accessed: 11.07.2025).

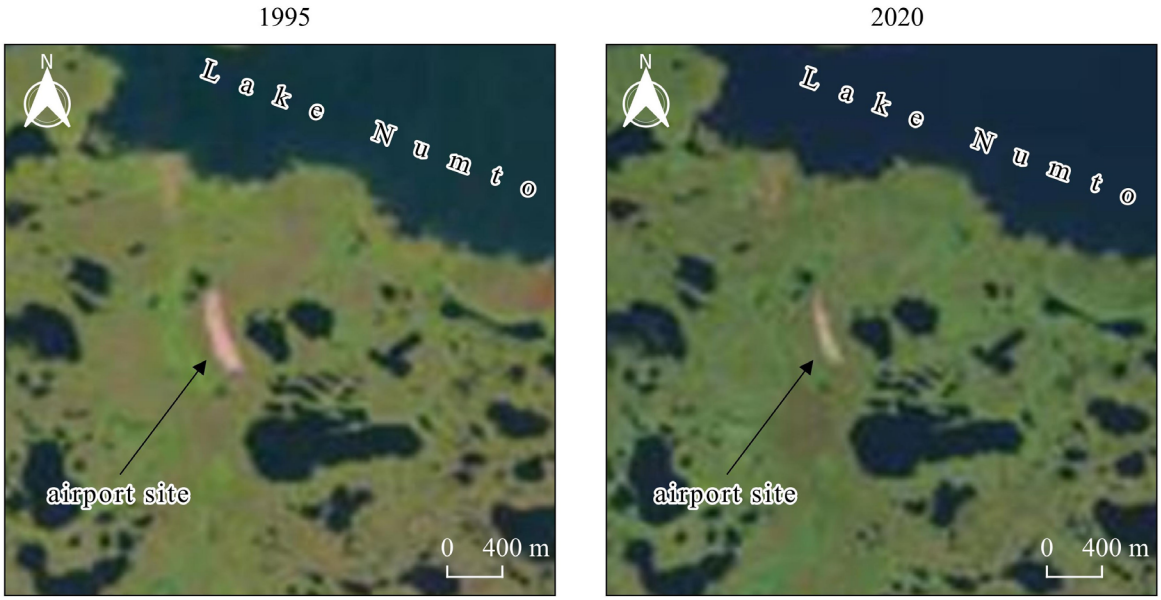

Fig. 1. Satellite images of the site location (Landsat 5-8 multi-spectral imaging data).

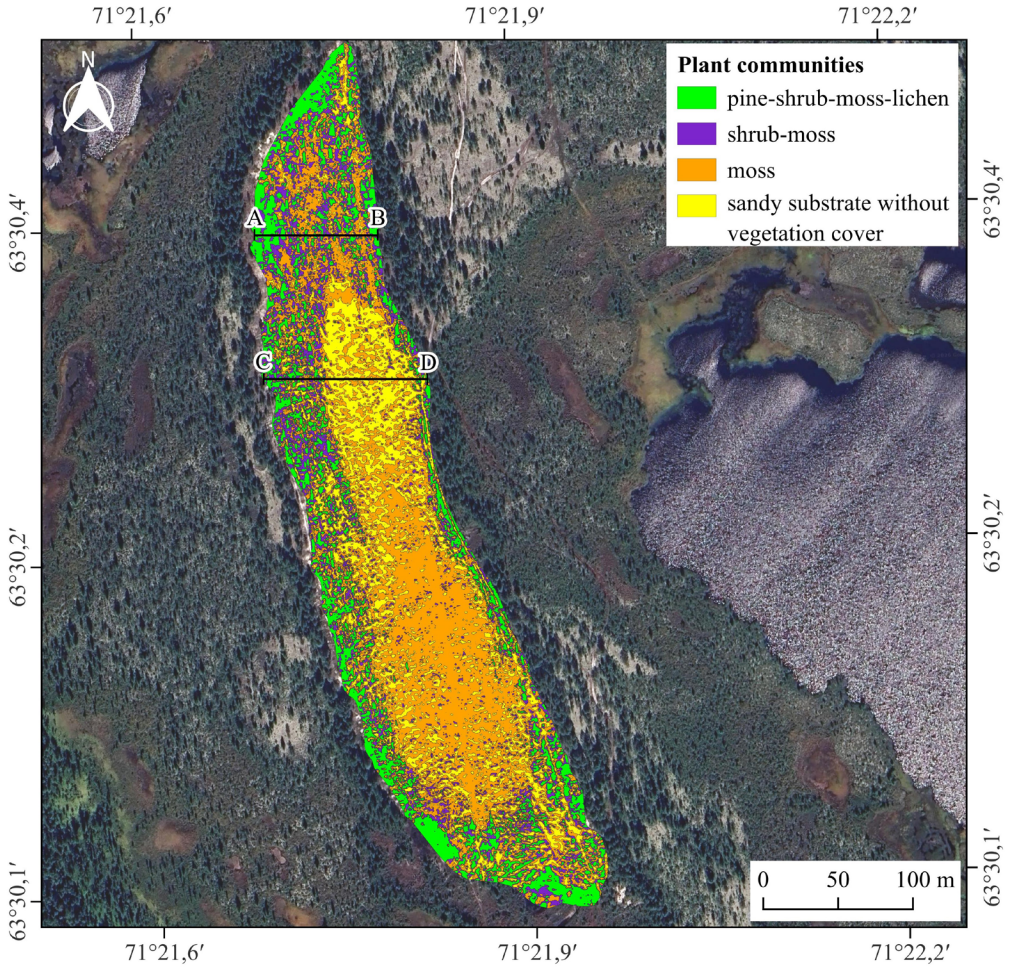

Fig. 2. Map of vegetation restoration on the overgrown airport site near Numto settlement, 2024: AB, CD – geobotanical profiles.

Remote analysis of vegetation restoration dynamics was conducted using Landsat 5–9 multispectral satellite imagery (30 m/pixel spatial resolution) for 1993 (the first data on the site's emergence), 2001, 2013, and 2024 during late growing season (early to mid-August). The disturbance index DI was used, reflecting the spectral signatures of the forest vegetation absence and their differences from the native forest stand of undisturbed areas (Healey et al., 2005). This index is calculated based on the ratio of scaled values of three orthogonal components (brightness (B), greenness (G), and wetness (W)) obtained by linear transformation of satellite images using the Tasseled Cap Transformation, TCT (Crist and Cicone, 1984):

$$DI = B_r - (G_r + W_r),$$

where B_r, G_r and W_r are the scaled values of brightness, greenness, and wetness.

Scaling is performed by using three equations:

$$B_r = (B - B_\mu)/B_\sigma,$$

$$G_r = (G - G_\mu)/G_\sigma,$$

$$W_r = (W - W_\mu)/W_\sigma,$$

where B, G and W are pixel values; B_μ, G_μ and W_μ – mean values for undisturbed forest; B_σ, G_σ and W_σ – standard deviations.

The use of scaled values in calculating the index allows for effective tracking of changes in forest vegetation and minimizes the impact of seasonal changes (Hilker et al., 2009; Masek et al., 2008). Disturbed areas are identified by higher values of "brightness" and low values of "greenness" and "wetness" (Baumann et al., 2014).

Intensive natural restoration with uneven vegetation cover may distort DI values (Rogan and Mietkiewicz, 2015). Therefore, in our study, we used a modified DI′ index, when the "greenness" component is not considered:

$$DI' = W_r - B_r$$

The modified index has higher accuracy due to its high sensitivity to discrete disturbances of vegetation, such as cutting, windfalls, etc. (Hais et al., 2009). The obtained index values were converted to positive values for easier data processing.

Spatiotemporal changes in the amount of photosynthetically active biomass in disturbed areas were monitored using normalized difference vegetation index (NDVI)[3]. The combined use of NDVI and DI has been successfully applied in a number of studies (Elsakov, 2014; Kaverin et al., 2016; Zhao et al., 2023). The data are presented as mean ± standard deviation.

Results and discussion

The site for the airport, originally a pine-lichen forest, was cleared in 1993, and the vegetation was removed completely. Construction was then suspended. Construction equipment remained on the site until 1997 and was later removed. The 5.51-hectare site has trapezoidal shape, oriented northwest to southeast, its length ranges 480 to 585 m, width, 75 to 120 m (Figs. 1, 2). The site is adjacent to pine-shrub-lichen forest and lake-marsh complexes; the latter are located to the northwest and east. Since 1997, the site has been virtually unaffected by any additional anthropogenic impact. It is occasionally used by the local population for transit passage on snowmobiles, also in summer.

[3] GIS-lab. Web page. URL: https://gis-lab.info/qa/ndvi.html?ysclid=ln1lbsrjpo707462178 (accessed: 21.07.2025).

Plant communities according to in situ studies

The site is being overgrown with pioneer species of mosses and dwarf shrubs; this process is most active along the site's periphery, in the areas bordering forest-marsh vegetation. When comparing satellite images from the mid-1990s and 2020s, total area occupied by various vegetation groups has increased significantly, and the boundaries of the sandy surface have reduced (Fig. 1). This is also confirmed by the results of geoinformation analysis: the decipherable area of disturbance has decreased by 23%.

Wind erosion prevents the site from rapidly becoming overgrown, removing sand from the areas with no vegetation. In the areas, where soil is anchored by the root system of dwarf shrubs (crowberries), sand is retained and trapped, forming a distinctive microrelief of hummocks (1–2 m diameter), alternating with depressions devoid of vegetation or with only moss patches.

Data obtained during field observations and geobotanical descriptions suggest a successful process of self-restoration of vegetation on the overgrown site. The overgrowth process occurs from the periphery to the center, primarily from west to east, which is likely related to the prevailing wind direction throughout the year. A very limited number of native plant species, resistant to extreme environmental conditions (insufficient moisture and sandy substrate shifts), participate in the overgrowing. In particular, 18 species were identified (16 vascular plants, 1 lichen, and 1 bryophyte) in 2001, while there were only 14 species (8 vascular plants, 5 lichens, and 1 bryophyte) registered in 2024. Alien species are absent. The geobotanical descriptions are summarized in tables (Tables 1, 2). A floristic survey of the entire site in 2024 did not reveal any additional species that were not included in the earlier geobotanical descriptions (Table 2).

Based on satellite images and in situ observations in 2024, a vegetation map was developed (Fig. 2) and 4 stages of site overgrowth were identified (Fig. 3):

1. Sandy substrate without vegetation cover – 1.15 ha (20.9% of the total area);
2. Moss – 2.36 ha, 42.9% (Fig. 3**A**);
3. Shrub-moss – 1.01 ha, 18.2% (Fig. 3**B**);
4. Pine-shrub-moss-lichen – 0.99 ha, 18.0% (Fig. 3 **C**, **D**).

Pioneer vegetation on a sandy substrate is represented by one species of moss, bog haircap moss *Polytrichum strictum*, forming the spots on minor increases in the microrelief – flat hillocks up to 15–20-cm high (Fig. 3**A**). Moss patches are constantly exposed to shifting sand, so the share of non-overgrown patches fluctuates. Currently, moss patches are the most abundant in terms of occupying area (almost 43%). Observations in similar areas indicate that another moss species, bristly haircap *Polytrichum piliferum* Hedw., plays a significant role in sand stabilization during the early stages of overgrowth (Kapitonova et al., 2017; Koneva and Lashchinsky, 2014). The predominance of one or another species is likely due to its presence in adjacent areas and the humidity of the habitat. In sand quarries, bog haircap moss *P. strictum* is one of the pioneer species that overgrows humid surface depressions (Sizov and Lobotrosova, 2016).

The communities of the next stage of succession are formed due to the shrubs settling on the hillocks. There, crowberry *Empetrum nigrum* predominates; lingonberry *Vaccinium vitis-idaea* and marsh Labrador tea *Rhododendron tomentosum* join occasionally. These species anchor the sandy substrate by their root systems. This results in the formation of higher hillocks (40–50 cm and even higher) covered with shrub and shrub-moss vegetation, alternating with lower "moss" hillocks and the areas with no vegetation (Fig. 3**B**). The role of crowberry in sand stabilization has been previously noted (Koneva and Lashchinsky, 2014); however, the formation of sand hillocks covered with crowberry is a rare occurrence. The structure and formation of such "crowberry" hillocks on sandy deposits in subarctic conditions has been studied in detail on the Kola Peninsula (Zakharchenko et al., 2010).

Scots pine *Pinus sylvestris* settles on the formed hillocks located closer to the periphery of the site and between them. Consequently, lichen patches appear, species diversity and the degree of projective cover of the grass-shrub and moss-lichen layers increase (Fig. 3**C**). The tree height varies from 0.5 m in the central part of the site to 2(4) m in the peripheral part.

The areas occupied by newly formed pine-shrub-moss-lichen communities locate closer to the boundaries of the site, especially in the western part (Fig. 3**D**). The area pattern across the site is apparently determined by the prevalence of westerly and southwesterly winds throughout the year. Here, the tree height reaches 7–8 m, with Scots pine *Pinus sylvestris* predominating; 1–4 m high downy

Table 1. Descriptions of the overgrown area, sites nos. 1–10; June 27, 2001

No.	Species	Total coverage, points	Coverage, points for 20 × 50 cm sample plots along the transect									
			1	2	3	4	5	6	7	8	9	10
1	*Betula nana* L.	2										
2	*Betula pubescens* Ehrh.	2										
3	*Pinus sibirica* Du Tour	1										
4	*Pinus sylvestris* L.	1										
5	*Sorbus aucuparia* L. subsp. *glabrata* (Wimm. & Grab.) Hedl.	1										
6	*Carex globularis* L.	2										
7	*Carex rotundata* Wahlenb.	1										
8	*Carex* sp.	1										
9	*Epilobium angustifolium* L.	1–3										
10	*Empetrum nigrum* L.	3			2			3			2	
11	*Eriophorum angustifolium* Honck. subsp. *angustifolium*	1										
12	*Eriophorum scheuchzerii* Hoppe	1										
13	*Rhododendron tomentosum* Harmaja	2										
14	*Vaccinium myrtillus* L.	1										
15	*Vaccinium uliginosum* L.	1										
16	*Vaccinium vitis-idaea* L.	5		1	2	2		2	1		2	1
17	*Cladonia stellaris* (Opiz) Pouzar & Vězda	1										
18	*Polytrichum strictum* Menzies ex Brid.	3–5	2	3	3	2	3			1	2	4
	Total	**18**	**1**	**2**	**3**	**2**	**1**	**2**	**1**	**1**	**3**	**2**

Table 2. Descriptions of the overgrown area, sites nos.1–5; August 31. 2024.

No.	Species	Coverage, points; values in brackets indicate coverage in %; tree height (m) is indicated for trees and shrubs.				
		1	2	3	4	5
1	*Betula nana* L.			1		
2	*Betula pubescens* Ehrh.	2 m	1–4 m	1–4 m		
3	*Pinus sibirica* Du Tour	0.5 m	0.2 m			
4	*Pinus sylvestris* L.	5–7 m	1.5–8 m	1.5–6 m	2–4 m	0.8 m
5	*Empetrum nigrum* L.	2 (15)	2 (10)	2 (20)	3 (35)	2 (15)
6	*Rhododendron tomentosum* Harmaja	+ (< 1)	1 (1)	1 (< 5)	1 (5)	
7	*Vaccinium uliginosum* L.			1 (1)	R (< 1)	
8	*Vaccinium vitis-idaea* L.	1 (5)	1 (5)	1 (< 5)	1 (5)	1 (1)
9	*Polytrichum strictum* Menzies ex Brid.	1 (5)	4 (60)		2 (15)	2 (15)
10	*Cladonia coccifera* (L.) Willd.		1 (< 5)	1 (< 5)	+ (< 1)	
11	*Cladonia deformis* (L.) Hoffm.			2 (20)	1 (5)	
12	*Cladonia stellaris* (Opiz) Pouzar & Vězda	1 (< 5)	1 (5)	1 (< 5)		
13	*Cladonia uncialis* (L.) Weber ex F.H. Wigg.		+ (< 1)		1 (< 5)	
14	*Flavocetraria nivalis* (L.) Kärnefelt et Thell	+ (< 1)	1 (1)	1 (1)	1 (1)	
	Total	**9**	**11**	**11**	**10**	**4**

birch *Betula pubescens* and single specimens of Siberian pine *Pinus sibirica* (up to 0.2 m) are found as well. The basis of the shrub layer is represented by dominating crowberry *Empetrum nigrum*, some marsh Labrador tea *Rhododendron tomentosum* and lingonberry *Vaccinium vitis-idaea*, and, rarely, bog bilberry *V. uliginosum* (< 1%). Dwarf birch *Betula nana* is found along the edge of the site. The projective cover of the moss-lichen layer reaches 70–75%. This layer has a mosaic structure with different ratios of species. Bog haircap moss *Polytrichum strictum* occupies from 5 to 60% of the area. Lichens are represented by several species, including typical species of non-overgrown substrates: *Cladonia deformis*, *C. coccifera*, *C. uncialis*, and *Flavocetraria nivalis.* Similar communities are formed on the slopes of overgrown sand quarries in the northern taiga of Western Siberia, where tree layer of Scots pine *Pinus sylvestris* and shrub-moss cover (lingonberry *Vaccinium vitis-idaea,* bog haircap moss *Polytrichum strictum*) are represented (Sizov and Lobotrosova, 2016).

Geobotanical profile AB, 85 m long, is located in the northern part of the site, where there are virtually no non-overgrown areas. On the western side, near the boundary with undisturbed forest-bog phytocenoses, the vegetation is represented by a birch-pine-dwarf shrub-moss-lichen community with a tree layer, where tree height may reach up to 7–8m (Fig. 4; Table 2, descriptions of sites nos. 1, 2). The soil is covered by dwarf shrub-moss-lichen communities comprising dwarf birch *Betula nana,* marsh Labrador tea *Rhododendron tomentosum,* and lingonberry *Vaccinium vitis-idaea.* Towards the central part of the site, the tree layer becomes increasingly sparse; birch is absent; pines' height is 2–4 m; crowberry *Empetrum nigrum* becomes the dominant species among the dwarf shrubs (on low hillocks);

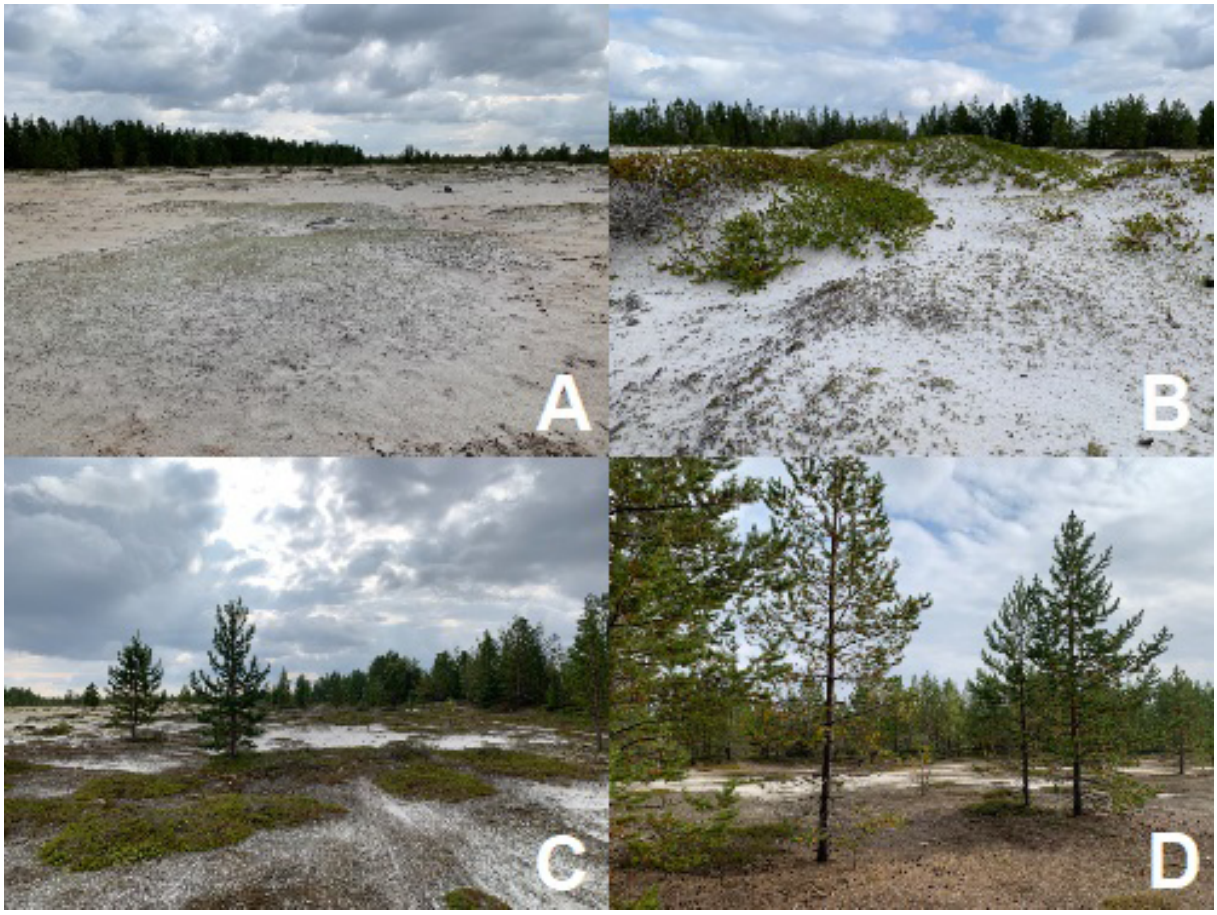

Fig. 3. Stages of site overgrowth: **A** – spots of bog haircap moss *Polytrichum strictum;* **B** – dwarf shrub-moss and moss vegetation with a hummocky microrelief; **C** – dwarf shrub-moss vegetation with single pine trees; **D** – formed pine-dwarf shrub-moss-lichen community in the peripheral part of the study site.

and the share of lichens decreases (Table 2, description of site no. 4). In the central part, the height of the "crowberry-moss" hillocks increases up to 50 cm, and pine trees no taller than 1 m are encountered sporadically. At the eastern boundary of the site, the vegetation composition and structure are similar to that at the western boundary, but with a lower pine tree layer (tree height < 4 m) and a virtually complete absence of lichens on the soil.

Profile CD, 110 m long, is located further south, its peripheral areas are similar to profile AB. On the eastern side, trees form a narrow strip (~10 m wide), but the tree layer is not developed in almost the entire central part (~80 m long). Here, low flat hillocks with moss vegetation (bog haircap moss *Polytrichum strictum* predominates) alternate with areas of non-overgrown sand. Higher hillocks with crowberry *Empetrum nigrum* are found singly, mainly on the border with pine-shrub-moss-lichen vegetation.

When comparing the data of 2001 and 2024, we found two directions of how vegetation cover was formed on the studied site: (1) a significant increase in the total area occupied by various groups of vegetation, and (2) a decrease in the diversity of pioneer flora species (Tables 1, 2). In 2001—2002, meteorological conditions were characterized by high precipitation and low air temperatures both in general for the year and during the summer period (Table 3). This contributed to the development of meso- and hygrophytic plant species on the site, which have subsequently disappeared in arid years with minimal precipitation and high temperatures (2006–2009), when the groundwater level and shallowing of Lake Numto occurred (Moskovchenko, 2017). In 2024, there were no mountain rowan *Sorbus aucuparia* subsp. *glabrata* and fireweed *Epilobium angustifolium* recorded, as well as a number of species characteristic of more humid substrates, such as globular sedge *Carex globularis*, roundfruit sedge *C. rotundata*, common cottongrass *Eriophorum angustifolium*, Scheuchzer's cottongrass *E. scheuchzeri*, and bilberry *Vaccinium myrtillus* (Table 1). Currently, these species are found only in the adjacent area, but their reappearance in the overgrown area cannot be ruled out in years with humid weather. The

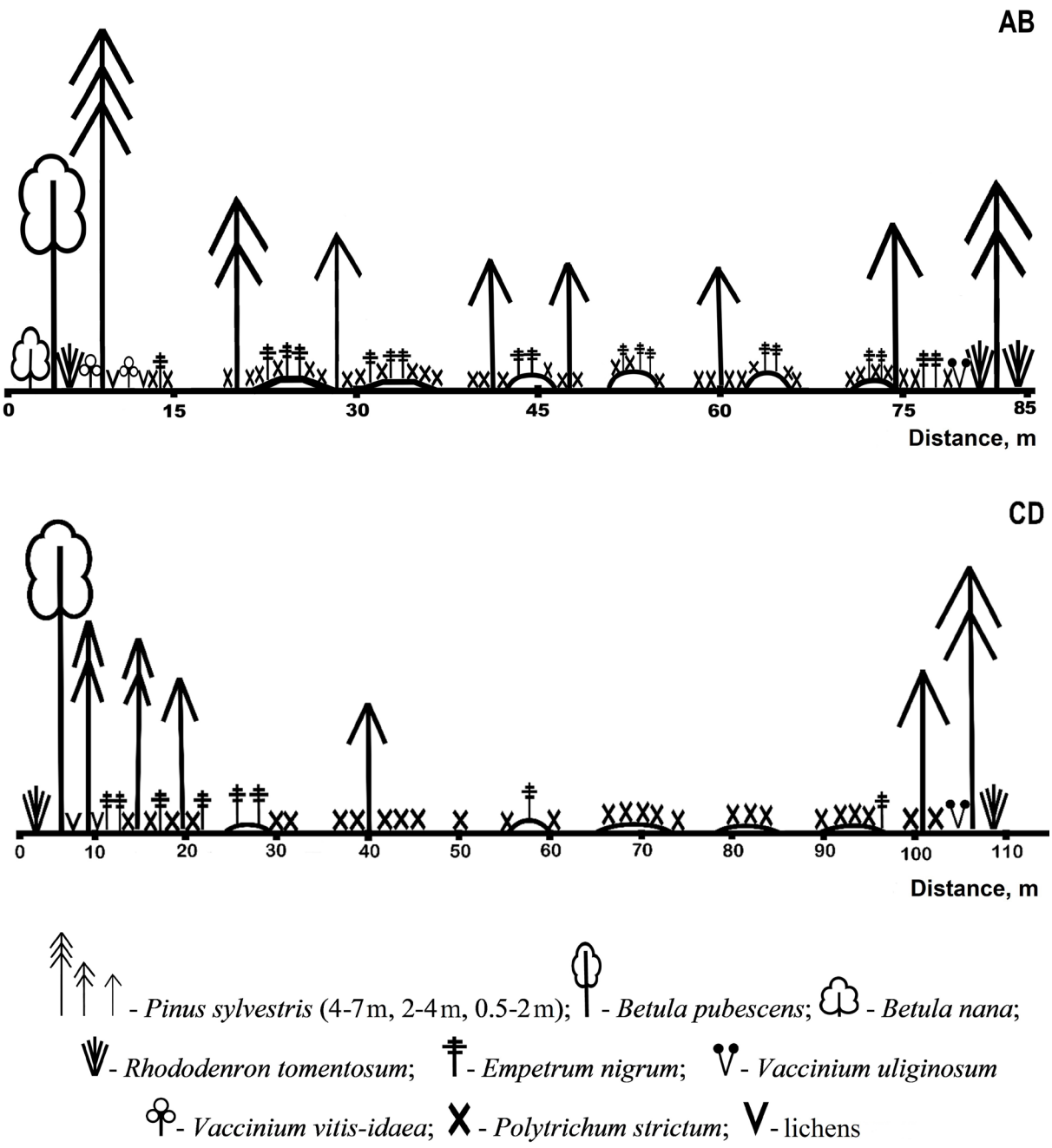

Fig. 4. Geobotanical profiles of the overgrown site.

presence of lingonberry *Vaccinium vitis-idaea* has significantly decreased, but both the lichen diversity and their cover area increased at the sites with a formed tree layer. Generally, the vegetation is now more xerophytic. Within the study area, there are herbaceous plant species characteristic of the initial stages of succession on a sandy substrate in the forest-tundra and northern taiga: these are wood small-reed *Calamagrostis epigejos* (L.) Roth, inhabiting similar environments, and highland rush *Oreojuncus trifidus* (L.) Záv. Drábk. & Kirschner, found in more humid habitats. Wood small-reed *Calamagrostis epigejos* is a Palearctic forest and meadow species, widespread in disturbed habitats. Highland rush *Oreojuncus trifidus* is an arctic-alpine species that is absent in natural northern taiga communities, but it is characterized by high growth rates on disturbed sandy substrates (Kapitonova et al., 2017; Koneva and Lashchinsky, 2014).

Taking into account the ongoing development of oil fields in the southern and central parts of the Numto Nature Park (the nearest oil production facilities are currently located at a distance of 20–30 km) and construction in Numto settlement, alien plant species may appear within the site in the near future, actively spreading through disturbed habitats (Glazunov and Nikolaenko, 2025).

Changes in vegetation cover according to remote sensing data

According to the DI′ values, the vegetation cover restoration rate remained quite low at the airport site over the past three decades. A consistent decrease of vegetation cover restoration rate been observed only since 2001 (Fig. 5), when humidity was lower comparing to the year the site was created. In particular, "wetness" index was −11.4 ± 2.55 in 1993 and −13.3 ± 2.85 in 2001. This affected the vegetation cover restoration rate, despite the maximum value of the "brightness" index at the beginning of the study period (16.1 ± 4.05 in 1993 versus 14.8 ± 3.73 in 2001). The slight change in vegetation cover restoration rate over the study period may be associated with small spectral differences between the surface of the disturbed site and the adjacent sparse pine lichen vegetation. According to S.P. Healey et al. (2005), a more pronounced contrast between the values is characteristic of areas with a predominance of dark coniferous species.

According to spatiotemporal analysis of DI′, vegetation develops more rapidly in peripheral areas bordering natural plant communities. By 2024, the index decreases in the marginal parts of the site, corresponding to the appearance of a greater number of pixels in green and blue shades (Fig. 6).

Table 3. Meteorological parameters and their linear trends in 1993–2024 in the study area. Dashes indicate no data available.

Year	Air temperature near the soil surface, °C					Precipitation amount, mms				
	winter	spring	summer	autumn	annual	winter	spring	summer	autumn	annual
1993	–18.3	–5.70	15.5	–4.70	–3.30	–	–	–	–	–
2001	–24.9	–3.67	14.0	–3.90	–4.10	79	187	243	137	660
2013	–21.6	–6.17	15.1	–1.23	–3.00	71	99	169	177	547
2024	–19.4	–6.37	15.4	1.00	–1.70	80	137	194	98	515
					Linear trend					
1993–2024	0.08	0.07	0.05	0.09	0.07	0.8	2.18	1.21	0.11	4.18

The opposite trend is demonstrated by NDVI with a minimum value in 2001 (0.13 ± 0.02) and a maximum in 2024 (0.23± 0.07). A negative high correlation is observed between DI′ and NDVI ($r \geq -0.97$; $p < 0.05$). Slightly more favorable conditions for vegetation development were noted in 1993 (0.14 ± 0.01) compared to 2021, which is also confirmed by the analysis of the "greenness" component (−5.66 ± 0.83 in 1993; −14.00 ± 2.70 in 2001). The change in NDVI is largely due to variations in the average annual surface air temperature ($r = 0.96$; $p < 0.05$), but summer temperature has a lesser effect on the variability of the vegetation index ($r = 0.50$). According to the NDVI values, positive restoration dynamics of native forest vegetation, adjacent to the site, are noted as early as since 1993: 0.46 ± 0.07 in 1993; 0.52 ± 0.07 in 2001; 0.57 ± 0.04 in 2013; 0.62 ± 0.06 in 2024. This trend is consistent with the increase of the vegetation index obtained in a number of studies on the taiga zone of Western Siberia (Botvich et al., 2023; Fakhretdinov, 2023; Titkova and Vinogradova, 2019). In addition, $NDVI_{max}$ trend maps (Miles and Esau, 2016) indicate that this area is one of the few territories in the region where index increase is observed (~10%).

In general, spectral analysis revealed improved vegetation growth conditions at the disturbed site, accompanied by a positive trend in surface air temperature and precipitation throughout the year. However, spontaneous restoration is accompanied by high spatial heterogeneity of plant communities, as indicated by an increase in the standard deviation of this parameter in the second half of the study period (Fig. 5). Similar results were obtained when studying vegetation succession in dry sand quarries in the northern taiga subzone of Western Siberia: it was underlined that lichen sparse forest areas varied significantly in plant biomass and that a decrease in NDVI was directly related to a decrease in forest density (Sizov, 2025).

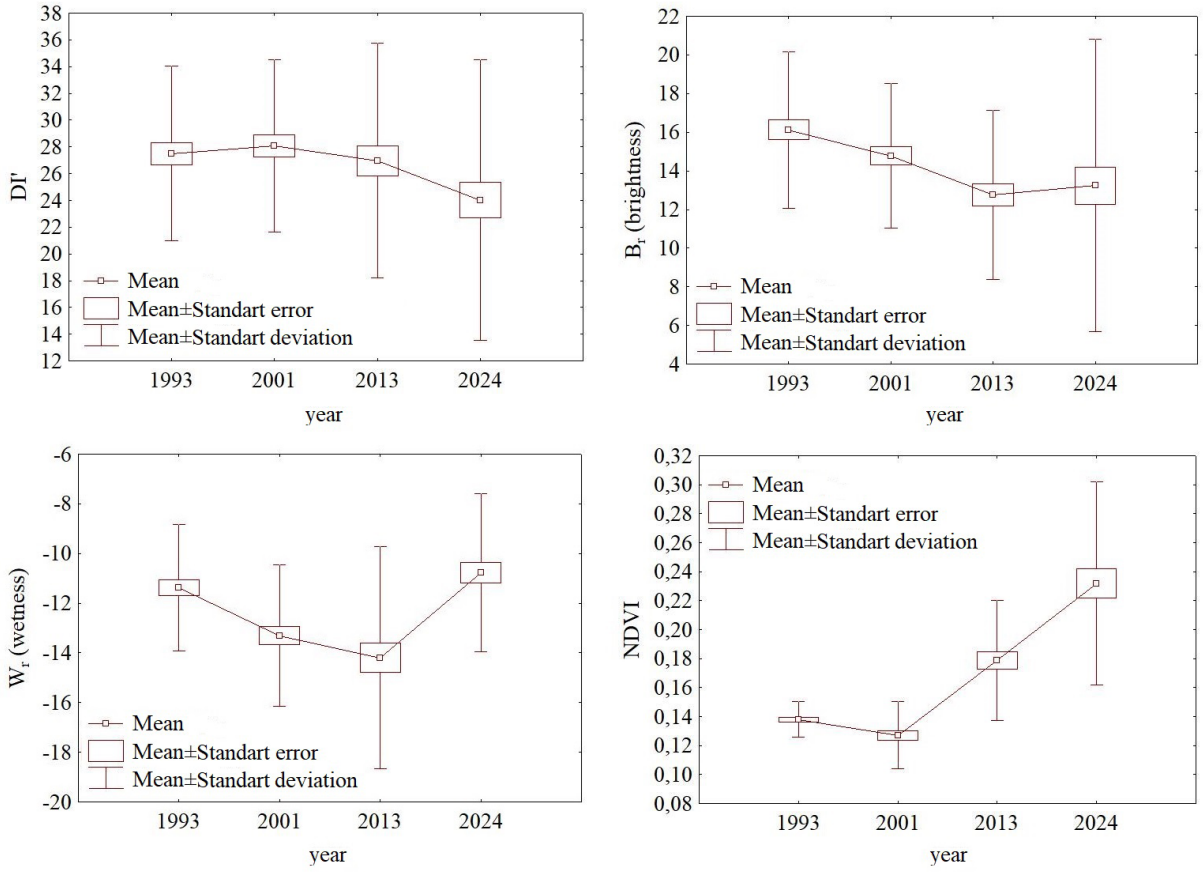

Fig. 5. Statistical parameters of spectral indicators of vegetation cover.

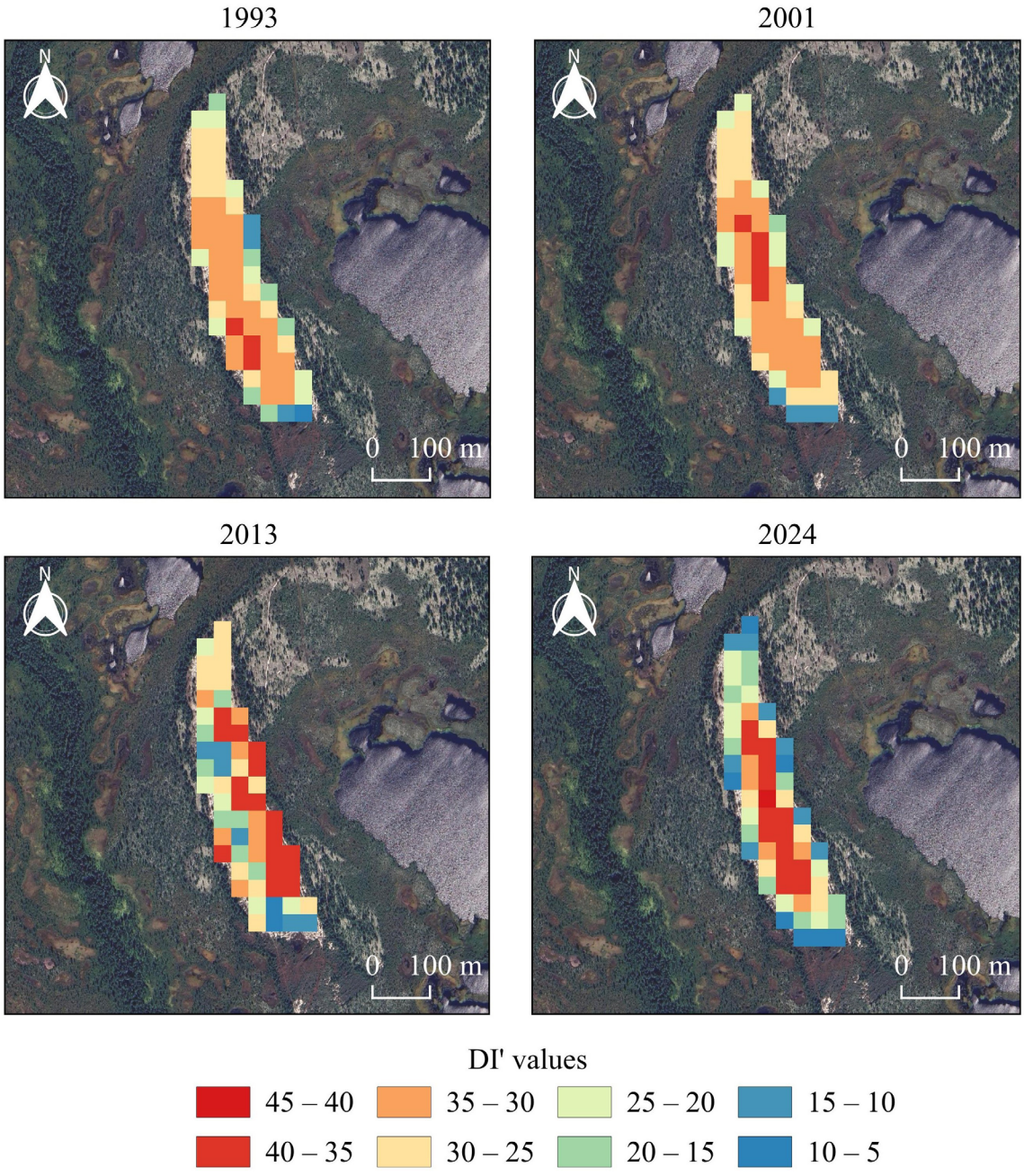

Fig. 6. Dynamics of DI′ values at the study site in 1993–2024.

Conclusions

The vegetation cover at the abandoned airport site near Numto settlement is characterized by self-restoration processes, which have been quite successful over the 30 years since the site was cleared and exposed sandy substrate emerged. By 2024, the total share of the areas without any plants was less than 21%. Four stages of sandy substrate overgrowth were identified: (1) no plants, (2) moss, (3) dwarf shrub-moss, and (4) pine-dwarf shrub-moss-lichen. The dominant pioneer species is bog haircap moss *Polytrichum strictum*, which forms patches of varying sizes in elevated microreliefs (hillocks); moss communities currently occupy more than 42% of the total area. Wind erosion, which removes and transports sand from uncovered areas, prevents more active overgrowth.

The next stage is associated with the shrubs' anchoring on the sand (mainly crowberry *Empetrum nigrum*) and with forming of higher hillocks overgrown by shrubs and mosses. Then, tree species (Scots pine *Pinus sylvestris*; rarely, downy birch *Betula pubescens*) and lichens appear; the species diversity and projective cover of the herbaceous-dwarf shrub and moss-lichen layers increase. The species composition of communities at the primary stages of overgrowth is affected by the surrounding forest-swamp communities of natural vegetation and includes a small number of species (from 1 to 11 per 100 m^2) of vascular plants, bryophytes and lichens capable of growing in extreme conditions of insufficient moisture on a sandy substrate. Meso- and hygrophytic plants that appeared on the site in relatively wet and cool years (globular sedge *Carex globularis,* roundfruit sedge *C. rotundata*, fireweed *Epilobium angustifolium*, common cottongrass *Eriophorum angustifolium*, Scheuchzer's cottongrass *E. scheuchzeri*, bilberry *Vaccinium myrtillus*) disappeared from plant communities in more arid conditions subsequently.

On the site periphery, pine-shrub-moss-lichen communities with a sparse tree layer (6–8 m high) are forming. Their plant species composition and structure are close to those of the natural original pine-shrub-lichen forest; currently, these communities occupy only 18% of the total area of the site.

The results of in situ geobotanical observations are in line with spectral indices obtained through satellite images: a weak trend in tree species restoration is evident from the small negative DI′ trend and increasing NDVI values. Even more comprehensive information is provided by examining the dynamics of individual components of this index ("brightness" and "wetness"). Generally, vegetation growth conditions are improving with positive trends in surface air temperature and precipitation throughout the year; however, the recorded amount of photosynthetically active biomass is currently lower comparing to background values. Vegetation restoration rate is higher in the areas adjacent to pristine forest and wetland phytocenoses.

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