Comparative multi-indicator satellite analysis of vegetation recovery in post-fire sandy coastal areas (case study of the Curonian Spit and Kinburn Peninsula)

Y. Shevchuk, O. Davydov, L. Bevainis

***Abstract*— The increasing frequency of wildfires in Eastern European sandy coastal environments necessitates reliable approaches for assessing post-fire vegetation recovery under conditions of high soil reflectance and sparse vegetation cover. These conditions often limit the efficacy of conventional single-index remote sensing methods. Comparative long-term assessments of post-fire recovery in sandy coastal systems under contrasting climatic conditions remain limited. This study evaluates post-fire vegetation dynamics in two geomorphologically similar but climatically contrasting coastal systems: the Curonian Spit (Lithuania) and the Kinburn Peninsula (Ukraine). A long-term, multi-index framework based on Landsat imagery (1984–2024) was applied using the Normalized Difference Vegetation Index (NDVI), Enhanced Vegetation Index, Soil-Adjusted Vegetation Index, Normalized Burn Ratio and Bare Soil Index to analyze vegetation recovery trajectories, recovery rates, and Normalized Recovery Index (NRI). The results indicated significant regional variations in post-fire succession. At the Smiltyne site, vegetation productivity exceeded pre-fire levels approximately 20-25 years after the 1995 wildfire, with NDVI increasing from ~0.165 to ~0.223 and NRI reaching 1.46. Conversely, recovery on the Kinburn Peninsula remained unfinished more than two decades following the 2001 fire (NRI = 0.38), indicating ongoing degradation of forest vegetation and transition toward less productive communities. The contrasting trajectories are primarily associated with climatic conditions and disturbance regimes. Recovery was faster and more complete in regions with higher humidity and managed reforestation, such as the Curonian Spit (650–750 mm/year). In contrast, ecosystem restoration on the Kinburn Peninsula (350–450 mm/year) was hindered by arid conditions, recurring disturbances, and limited regeneration capacity. The proposed multi-index framework provides a robust and transferable approach for long-term monitoring of post-fire vegetation recovery in sandy coastal environments affected by strong soil background effects. These findings underscore the significance of prolonged satellite monitoring for elucidating vegetation response processes and facilitating the development of management strategies in fire-affected coastal ecosystems.**

***Index Terms*— vegetation cover, post-fire recovery, Landsat, normalized difference vegetation index (NDVI), Kinburn Peninsula, Curonian Spit**

I. INTRODUCTION

OVER the past decades, forest fires have become one of the most significant natural and anthropogenic factors affecting ecosystems worldwide, particularly in arid regions such as the Mediterranean, Australia, the United States, and Eastern Europe [1], [6], [7], [9], [15], [40], [55]. Post-fire vegetation recovery is a complex ecological process driven by multiple interacting factors, including climate, fire severity, topography, and pre-fire vegetation composition [5], [7]. Sandy coastal ecosystems, characterized by limited water-holding capacity, high substrate reflectance and sensitive psammophytic plant communities, are particularly vulnerable to fire disturbances.

Remote sensing methods—particularly vegetation indices—provide a reliable foundation for monitoring vegetation dynamics across various geographic contexts. However, in sandy environments, the interpretation of satellite data is complicated by strong soil background effects, sparse vegetation cover, and pronounced spatial heterogeneity. These factors can significantly distort spectral signals and lead to biased assessments when conventional single-index approaches are applied [27], [50], [38]. To address these limitations, this

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study adopts a multi-indicator satellite-based approach that integrates several complementary spectral indices and incorporates pre-fire reference conditions [38].

While numerous studies have evaluated post-fire recovery using satellite imagery, comparative long-term studies focusing specifically on sandy coastal ecosystems under contrasting climatic and anthropogenic conditions remain limited. This study addresses this gap by directly comparing two geographically distant but morphologically similar regions.

The selection of the Curonian Spit (Lithuania) and the Kinburn Peninsula (Ukraine) as key study areas is driven by their high comparability in terms of geomorphological structure and artificial coniferous plantations, contrasted by their distinct climates (humid vs. arid) [2], [5], [9], [40], [46], [47], [51].

Vegetation recovery trends after wildfires are considered a key indicator of ecosystem response, influencing biodiversity patterns, stabilization of sandy substrates, and microclimatic regulation [24]. Remote sensing methods—particularly vegetation indices—provide a reliable foundation for monitoring vegetation dynamics [4], [18].

By combining indices sensitive to vegetation greenness, soil background, burn severity, and exposed substrates, the proposed framework aims to improve the robustness of post-fire recovery assessment in sandy coastal landscapes [19].

The aim of the study is to assess and compare post-fire vegetation recovery dynamics in two representative sandy coastal landscapes—the Curonian Spit and the Kinburn Peninsula—using long-term satellite observations and a multi-index analytical framework.

The main research objectives are:

1. To identify recovery trends and provide a quantitative assessment of post-fire vegetation dynamics;
2. To examine the relationship between the recovery rate and normalized spectral recovery as complementary indicators of post-fire vegetation response.

Previous studies [10], [15], [17], [18], [33], [45], [50], [53], have confirmed the effectiveness of remote sensing for analyzing post-fire vegetation dynamics across a wide range of geographic and climatic contexts. Nevertheless, comparative long-term studies focusing specifically on sandy coastal ecosystems under contrasting climatic and anthropogenic conditions remain limited which underscores the relevance of the present work.

II. Study area

The objects of this study are two barrier-type coastal sandy formations—the Curonian Spit (Lithuania) and the Kinburn Peninsula (Ukraine)—located on the shores of the Baltic and Black Seas, respectively (Fig. 1). Both sites are part of distinctive estuarine systems, separating brackish lagoons from open marine waters.

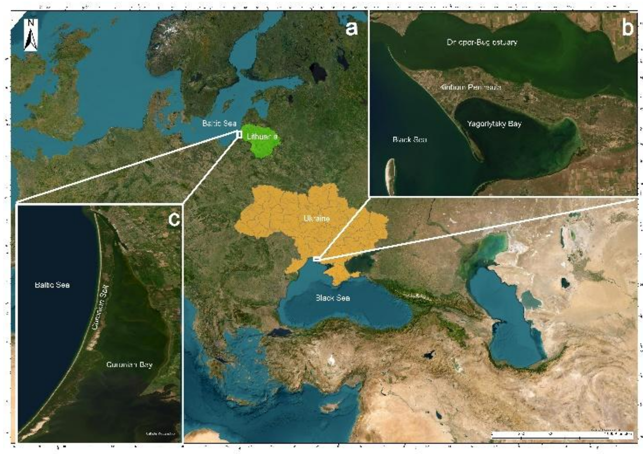

Fig. 1 Location of the Curonian Spit and the Kinburn Peninsula: a – within Eastern Europe and the coastlines of the Baltic and Black Seas; b – view of the Kinburn Peninsula; c – view of the Curonian Spit.

The Kinburn Peninsula, part of the Black Sea Lowland, is a T-shaped accumulative landform approximately 45 km long and covering an area of about 215 km² [32], [39]. It separates the Dnipro-Buh Estuary and Yagorlytsky Bay from the sea, features a low-lying relief (ranging from –0.4 to 14.3 m), and is subdivided into four sandy massifs separated by depressions [20].

The Curonian Spit, located in the southeastern part of the Baltic Sea, extends in an arc along the Curonian Lagoon and is approximately 99 km long, with an area of about 330 km² [21], [46]. The geomorphological structure of the spit includes five parallel coastal zones: the beach, foredune, deflation terrace (known as "palvė"), high dunes (up to 67.2 m), and lagoon terrace [22], [34], [45].

Despite morphological similarities, the genesis of these landforms differs: Kinburn was primarily formed by alluvial deposits from the Dnipro River [20], while the Curonian Spit developed through the accumulation of coastal-marine sediments driven by Baltic Sea level fluctuations [21]. In both cases, sandy deposits dominate, promoting the development of active aeolian processes [14], [16].

The climate in both regions is temperate-continental yet differs significantly between the two. Kinburn experiences hot and dry summers (up to 35 °C) and mild winters (around 0 °C), with 350–450 mm of annual precipitation occurring over ~90–120 rainy days, showing a more pronounced seasonal character with a spring-summer maximum.[32]. Historically, the area was dominated by psammophytic steppe interspersed with fragmented deciduous groves [20]. The Curonian Spit has warm summers (up to 25 °C) and moderately cool winters (0–5 °C), with total annual precipitation ranging from 700 to 800 mm distributed relatively evenly across ~170–190 rainy days per year. The surface of the spit was originally covered with mixed forests [22], [24], [25]. Thus, the Curonian Spit is characterized by frequent but less intense rainfall, whereas the Kinburn Peninsula experiences rarer, episodic, and intense precipitation events.

These climatic contrasts are expected to influence post-fire vegetation recovery trajectories, affecting both the rate and normalized of regeneration processes under otherwise comparable geological-geomorphological conditions.

Both sites have undergone substantial anthropogenic transformation, leading to intensified deflation processes. In Kinburn, this occurred in the 19th century due to overgrazing and deforestation. However, since the 1960s, large-scale plantations of Scots pine (*Pinus sylvestris*) and Crimean pine (*Pinus nigra subsp. pallasiana*) were established [32], [39], and by 2022, coniferous forests covered approximately 80% of the vegetated area [11], [29], [30], [31]. The Curonian Spit also experienced forest degradation since the 15th century: as a result of extensive logging, forest cover declined to 5–10%, triggering dune mobility. Since the 19th century, an afforestation program using mountain pine (*Pinus mugo*) has been implemented, stabilizing the landscape. Today, the forest cover of the spit is about 70%, with coniferous species comprising 83% of this area [3], [21].

Both study sites have experienced wildfire events over recent decades, although their fire regimes differ markedly. On the Kinburn Peninsula, wildfires have historically been associated with dry climatic conditions and anthropogenic pressures, with a pronounced increase in fire frequency and spatial extent observed since 2022. During the 1984–2024 observation period, fires were recorded almost annually in both regions (for instance, primarily in the Smiltynė area due to high recreational pressure in the warm season). However, these were generally small-scale, localized fires. For the purpose of this long-term comparative study, we specifically selected the most prominent, large-scale, stand-replacing fire events (1995, 2001, 2006, and 2014) because they had clearly delineated burn perimeters, enabling consistent satellite-based tracking [2], [9], [29], [30], [31] [32]. In contrast, the Curonian Spit is characterized by less frequent but ecologically significant fires, primarily affecting pine-dominated forest stands. The selected study areas represent sites impacted by well-documented fire events with clearly delineated burn perimeters, enabling consistent post-fire analysis using satellite data.

The relatively open structure of vegetation cover, dominance of sandy substrates, and limited topographic complexity of both landforms provide favorable conditions for long-term satellite-based monitoring. These characteristics support the consistent application of medium-resolution optical imagery, such as Landsat data, for assessing post-fire vegetation dynamics and surface condition changes over multi-decadal periods [35], [38].

The selection of the Kinburn Peninsula and the Curonian Spit as key study areas is driven by their high comparability in terms of geomorphological structure, lithological foundation, and vegetation cover. Both are accumulative forms composed of aeolian sands with high morphodynamic activity, historically stabilized by artificial coniferous plantations that now represent a high fire risk. A fundamental factor for comparing these sites via remote sensing is the high-water permeability and infiltration capacity of their sandy substrates. This physical property leads to rapid moisture drainage, meaning that post-fire vegetation response is determined more by the limited water retention of the substrate than by the absolute amount of regional precipitation. The differences in atmospheric precipitation between the two regions are partially mitigated by the high filtration capacity of the sand, the well-drained elevated surfaces, and the dominance of coniferous vegetation, which enhances rainfall interception. As a result, both sites function as systems with limited moisture availability. Their comparison provides a highly representative natural framework for satellite-based analysis, allowing us to separate the broader influence of climatic factors from the specific recovery mechanisms dictated by the underlying sandy surface.

III. Materials and Methods

The research design was based on a stepwise implementation of procedures for the acquisition, processing, and analysis of satellite data aimed at quantitatively assessing post-fire vegetation recovery. Each stage was structured to ensure the reproducibility, comparability, and scientific validity of the results across different study sites.

For the spatial analysis, four specific post-fire sites were selected across the two regions. On the Kinburn Peninsula, a site located between the villages of Pokrovka and Pokrovske (affected by a major wildfire in 2001, covering approx. 1600 ha) was chosen (Fig. 2). Within the Lithuanian part of the Curonian Spit, three distinct sites affected by fires of varying intensity and at different times were selected: the Smiltynė site (1995 fire, approx. 60 ha), the Alksnynė site (2006 fire, approx. 236 ha), and the Juodkrantė site (2014 fire, approx. 120 ha) (Fig. 3). Selecting these specific sites allows for the construction of multi-temporal datasets to analyze vegetation recovery phases across different post-fire timeframes.

A total of 53 satellite images from Landsat 5 and Landsat 8 (Level-2 processing, GeoTIFF format) were used for the analysis, all obtained via the USGS Earth Explorer platform. Radiometric comparability between Landsat 5 TM and Landsat 8 OLI data was ensured by using Level-2 surface reflectance products processed with sensor-specific atmospheric correction algorithms, along with consistent spectral index formulations applied across the entire time series. The temporal framework of analysis included: 20 years before the fire, the last image before the fire, immediately after the fire, one year after, and then at five-year intervals up to 2024. The exact observation years representing the pre-fire, fire event, and post-fire recovery stages for each specific study site are detailed in Supplementary Tables S1–S4. The imagery was processed in ArcGIS Pro: areas of interest were clipped from full scenes, including zones affected by wildfires [13], [38], [43], [49], [54].

In ArcGIS Pro, all scenes were processed using a uniform workflow that included spatial subsetting to predefined fire perimeters, verification of spatial alignment, and calculation of spectral indices from surface reflectance bands using raster algebra. Scene selection was based on minimal overall cloud cover followed by a rigorous visual inspection to ensure the complete absence of clouds and shadows within the fire perimeter polygons. Cloud- and shadow-contaminated scenes over the areas of interest were excluded from the analysis; therefore, no additional pixel-level masking was applied. The same preprocessing and index calculation workflow was consistently applied to all study sites.

The selection of spectral indices was based on their complementary sensitivity to various mechanisms of post-fire vegetation recovery in sandy environments. On the prepared raster images, five spectral indices were calculated—NDVI (Normalized Difference Vegetation Index) was chosen as the baseline indicator of overall photosynthetic activity [42]. To address its known limitations (e.g., saturation in dense canopies and sensitivity to soil background), EVI (Enhanced Vegetation Index) was included to improve robustness in high-density vegetation [26], while SAVI (Soil Adjusted Vegetation Index) was applied to explicitly compensate for the high reflectance of bare sandy soils typical of the early post-fire stages [27]. In addition, BSI (Bare Soil Index) was used to identify degraded areas and monitor the exposure of the sandy substrate [36], and NBR (Normalized Burn Ratio) was selected to evaluate burn severity and track the transition from burned surfaces to regenerating vegetation [10], [23], [26], [28], [42]. Formulas, band assignments for Landsat 5/8, and purposes are below (formulas 1-5).:

$$NDVI = \frac{(NIR-RED)}{(NIR+RED)} \quad (1),$$

Bands: Landsat 5 — Red=Band 3, NIR=Band 4; Landsat 8 — Red=Band 4, NIR=Band 5. Purpose: overall vegetation greenness/biomass.

$$EVI = G\frac{(NIR-Red)}{(NIR+C1*Red-C2*Blue+L)} \quad (2),$$

In these equations, G = 2.5, L = 1, C_1 = 6 and C_2 = 7.5. Bands: Landsat 5 — Red=Band 3, NIR=Band 4, Blue=Band 1; Landsat 8 — Red=Band 4, NIR=Band 5, Blue=Band 2. Purpose: improved sensitivity in dense vegetation and over bright soils.

$$\mathrm{SAVI} = \frac{\mathrm{NIR-Red*(1+L)}}{\mathrm{(NIR+Red+L)}} \quad (3),$$

In these equations, L = 0.5. Bands: Landsat 5 — Red=Band 3, NIR=Band 4; Landsat 8 — Red=Band 4, NIR=Band 5. Purpose: mitigate soil brightness (relevant for sandy systems) [27].

$$BSI = \frac{(Green+Blue)-(Red+NIR)}{(Green+Blue+Red+NIR)} \quad (4),$$

Bands: Landsat 5 — Red=Band 3, Green=Band 2, Blue=Band 1, NIR=Band 4; Landsat 8 — Red=Band 4, Green=Band 3, Blue=Band 2, NIR=Band 5. Purpose: assess soil exposure/vegetation damage after fire.

$$NBR = \frac{(NIR-SWIR)}{(NIR+SWIR)} \quad (5),$$

Bands: Landsat 5 — NIR=Band 4, SWIR=Band 5; Landsat 8 — NIR=Band 5, SWIR=Band 7. Purpose: evaluate burn severity.

As a result, the indices were aggregated as mean values for each site and observation date. The data were imported into RStudio, where time series of vegetation activity were constructed.

Archived NDVI data covering a 20-year period were used to analyze the pre-fire condition. Values were cleaned of artifacts (e.g., cloud cover, shadow) and used to calculate reference characteristics in two steps:

1. Analysis based on the 10th and 90th percentiles of vegetation productivity distribution;
2. Calculation of mean NDVI values as an integrated measure of ecosystem productivity.

Comparison of reference values with post-fire data enabled the tracking of vegetation recovery dynamics over time. We performed a quantitative assessment of the recovery rate and normalized spectral recovery relative to the pre-fire condition using Equations (6) and (7). Equations (6) and (7) were formulated by the authors for this study as simple comparative metrics, but they are not proposed as new universal methodological equations. They are based on the commonly used remote-sensing logic of comparing post-fire spectral conditions with pre-fire reference levels and expressing recovery either as a relative normalized value or as an average annual rate of spectral change [17], [18], [33], [38].

Normalized Recovery Index (Relative Recovery):

$$NRI = \frac{\mathrm{Index_{2024}-Index_{post}}}{\mathrm{Index_{pre}-Index_{post}}} \quad (6)$$

where $\mathrm{Index_{2024}}$ is the index value in the final observation year (2024), $\mathrm{Index_{post}}$ is the immediate post-fire reference (calculated as a robust mean during the first post-fire season), and $\mathrm{Index_{pre}}$ is the pre-fire reference (calculated as the mean over several pre-fire years). This standard normalization ensures a positive denominator and allows vegetation recovery to be expressed as a relative metric, thereby enabling comparison between sites with differing baseline productivity levels and recovery trajectories. An NRI value of 0 corresponds to the immediate post-fire state, while a value of 1 indicates a return to the pre-fire reference. Conceptually and mathematically, this approach aligns with standard normalized recovery measures and relative recovery indices commonly applied in post-fire remote sensing studies, relying on robust mean estimates rather than extreme minimum/maximum values to reduce the influence of outliers [17], [18], [33].

Recovery rate (trend analysis):

$$\text{Recovery Rate} = \frac{\mathrm{Index_{2024}} - \mathrm{Index_{fire}}}{\text{number of years since the fire}} \quad (7)$$

Together, these metrics provide quantitative indicators describing both the rate and the relative magnitude of post-fire vegetation recovery. An exploratory Pearson correlation [37] analysis between recovery rate and normalized recovery was performed in RStudio [41] to examine their relationship within the analyzed dataset . The final stage was a comparative analysis of the study sites, incorporating statistical comparison of recovery trends, climatic and hydrological maps and documented afforestation practices (as contextual background).

IV. Results

A. Natural Conditions and Spatiotemporal Characteristics of Wildfires

This study focused on two sites with similar natural conditions, both dominated by artificial pine forests planted to stabilize sandy surfaces. The primary focus was on areas where portions of the forest stands were damaged by wildfires.

For analysis, a site was selected in the western part of the Kinburn Peninsula, located between the villages of Pokrovka and Pokrovske, with a total area of approximately 1600 ha, affected by a major wildfire in 2001 (Fig. 2).

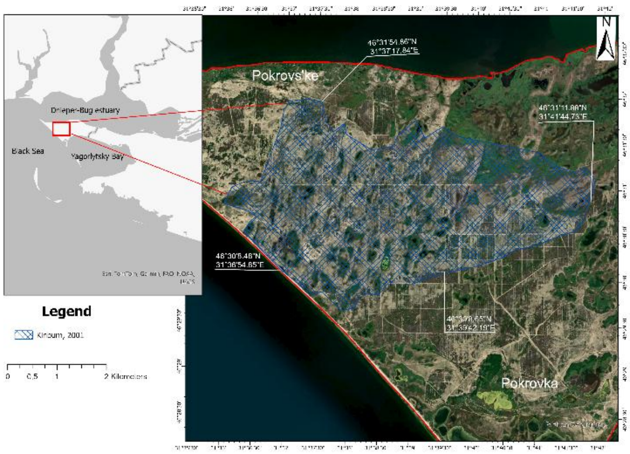

Fig. 2 Geographic location of the post-fire site between Pokrovka and Pokrovs'ke villages, Kinburn Peninsula (2001 wildfire). The background is the high-resolution Esri World Imagery basemap.

The main part of this area was occupied by pine forest stands (950.84 ha), with additional areas comprising broadleaf forests (≈80 ha), steppe and semi-steppe vegetation (≈250 ha), and wetlands (≈320 ha).

Within the Lithuanian part of the Curonian Spit, three sites affected by fires of varying intensity and at different times were selected: Smiltynė, Alksnynė, and Juodkrantė (Fig. 3).

The Smiltynė site was affected by a wildfire in 1995, covering an area of approximately 60 ha, predominantly composed of pine forest.

The Alksnynė site was burned in 2006, covering around 236 ha, with pine (≈230 ha) and broadleaf forests, as well as grasslands.

The Juodkrantė site experienced a wildfire in 2014, with a total area of about 120 ha, consisting of coniferous vegetation (≈110 ha) and herbaceous cover (≈10 ha).

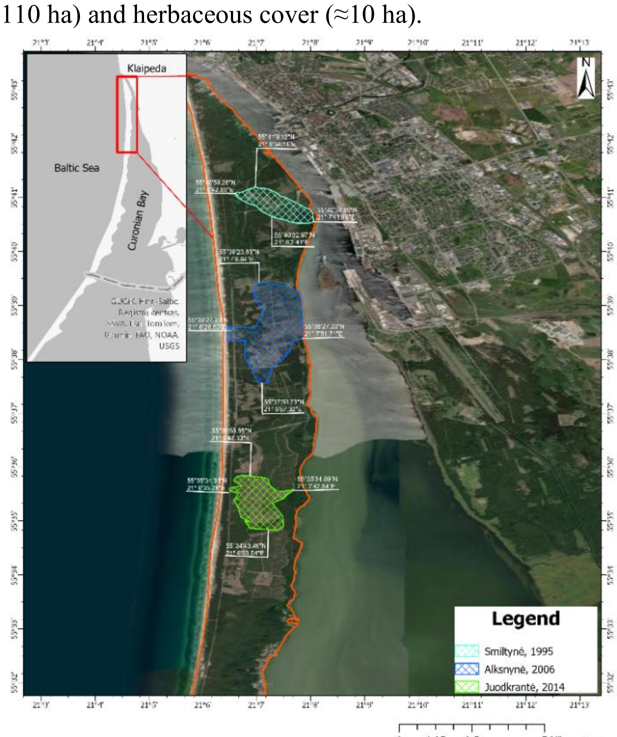

Fig. 3. Map of fire-affected sites on the Curonian Spit: Smiltynė (1995 fire), Alksnynė (2006 fire), and Juodkrantė (2014 fire). The background is the high-resolution Esri World Imagery basemap.

The selection of specific sites was based on the occurrence of documented large-scale wildfires of varying intensity and in different years—1995, 2001, 2006, and 2014—which allows the construction of multi-temporal datasets for analyzing vegetation recovery phases. All sites are well represented in the Landsat satellite archives, with sufficient imagery before and after the fire events—an essential prerequisite for calculating spectral indices and conducting temporal change analysis.

Exact numerical values of spectral indices used in the analyses presented in Sections B–D are provided in Supplementary Tables S1–S4.The selected sites are representative of post-fire processes in coastal pine forest ecosystems of Eastern Europe.

B. Assessment of vegetation recovery rates in post-fire areas using spectral indices

To assess vegetation recovery dynamics in post-fire areas, spectral indices were calculated based on satellite imagery for selected time intervals.

Kinburn Site. The analysis for the Kinburn Peninsula (Fig. 2) showed a sharp decline in NDVI from 0.18 to 0.04 after the fire, indicating significant destruction of vegetation cover. One year after the fire, the initial recovery phase began, primarily driven by heliophilous species, with the mean NDVI rising to 0.11. In the following years, a steady increase in NDVI was observed, reaching 0.14 by 2011, indicating partial vegetation recovery. From 2016 to 2021, vegetation covers stabilized and continued to develop, with coniferous species partially replaced by shrubs and broadleaf species. Coniferous cover partially recovered due to artificial reforestation efforts. Since 2022, a decline in NDVI was observed, with values decreasing to approximately 0.14 by 2024 (Fig. 4).

The EVI showed a similar trend. The highest EVI recovery rates were recorded during 2016–2021, with an average annual increase of approximately 0.0124, reflecting the recovery of dense vegetation and ecosystem stabilization (Fig. 4). SAVI (which accounts for soil background) indicated significant recovery of herbaceous and shrub communities, particularly in areas with sparse vegetation. Its dynamics reflected a more pronounced recovery trend than NDVI starting in 2016. The NBR index confirmed severe fire impact, with values declining to minimal positive levels by 2016. Recovery based on this index began approximately 15 years after the fire, with values comparable to pre-fire levels observed between 2011 and 2016 (Fig. 4). The BSI increased immediately after the fire, indicating exposed sandy substrate. In subsequent years, BSI values gradually declined, indicating recovery of protective soil cover and vegetation return on degraded areas (Fig. 4). Vegetation recovery on the Kinburn Peninsula over the two decades following the fire can be characterized as gradual, with the highest intensity between 2016 and 2021 (Fig. 5).

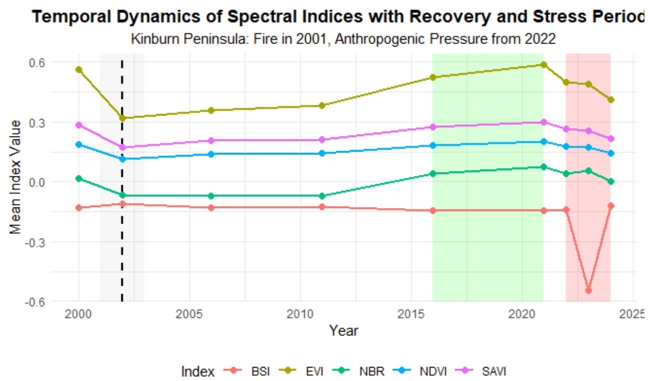

Fig. 4 Long-term dynamics of average spectral index values at the Kinburn site affected by fire within the Kinburn Peninsula. The grey background with a dashed line indicates the fire event; the green background highlights the period of active vegetation recovery (2016–2021); and the pink background denotes the recent period of anthropogenic stress and vegetation degradation (2022–2024).Numerical values used to construct the time series are provided in Table S1 (Supplementary Material)

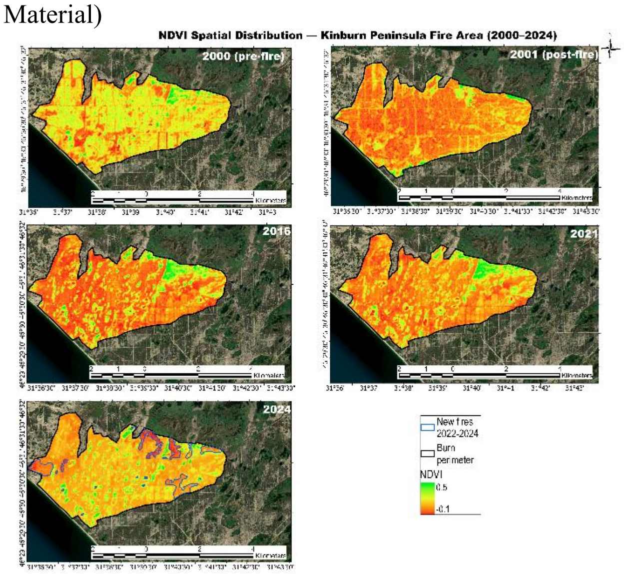

Fig. 5 Spatial distribution of NDVI at various stages of restoration in the Kinburn area within the Kinburn Peninsula

Smiltynė Site. The analysis of the Smiltynė site revealed that pre-fire mean NDVI values were 0.165, indicating a stable state of vegetation cover. In 1995, following the wildfire, NDVI decreased to 0.154, indicating partial vegetation degradation (Fig. 6). In the following years, a positive recovery trend was observed. By 2010, the NDVI value had reached 0.162, nearing pre-fire levels. In 2020, NDVI increased to 0.206, and by 2024 it reached 0.223, exceeding the pre-fire values (Fig. 6). The average annual NDVI increase during the active recovery period (2015–2020) was 0.00105, reflecting a steady yet moderate recovery in productivity. The EVI index showed a more pronounced recovery, with an average annual increase of 0.0055 over the same period. SAVI and BSI confirmed the recovery of herbaceous and shrub vegetation in sparsely vegetated areas, as well as a reduction in bare sandy soil exposure. The NBR index, used to assess fire impact, showed a sharp decline in 1995 and gradual recovery in the following years (Fig. 6). These results indicate a stable post-firerecovery trend the Smiltynė site during 2015–2024 (Fig. 7).

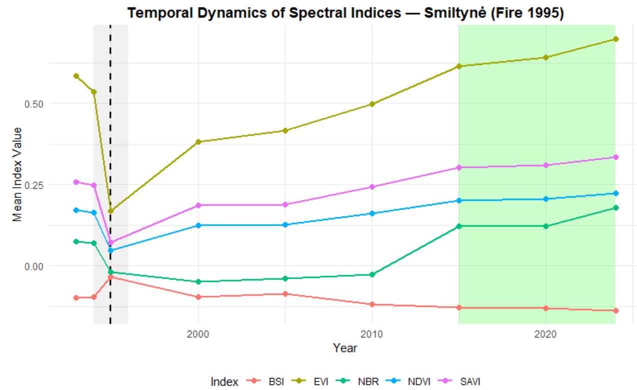

Fig. 6 Long-term dynamics of average spectral index values at the Smiltynė site affected by fire within the Curonian Spit. The grey background with a dashed line indicates the fire event, while the green background highlights the period of stable vegetation recovery.Numerical values used to construct the time series are provided in Table S2 (Supplementary Material)

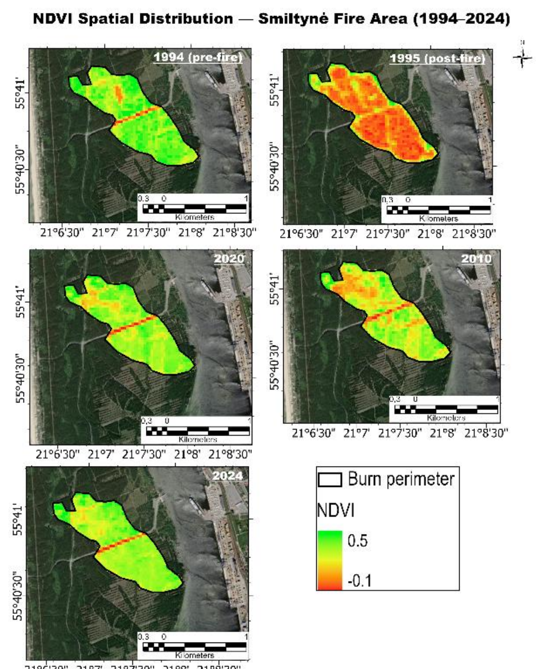

Fig. 7 Spatial distribution of NDVI at various stages of recovery in the Smiltynė area affected by fire within the Curonian Spit

Alksnynė Site. The analysis of the Alksnynė site showed a pre-fire mean NDVI of 0.176, indicating a stable vegetation condition. In 2006, immediately after the fire, NDVI dropped to 0.062, reflecting a sharp reduction in photosynthetically active biomass (Fig. 8). Recovery began as early as 2007, but the most significant positive trend was recorded in the subsequent years. By 2016, NDVI reached 0.167, and by 2021 — 0.228, indicating active vegetation regeneration. As of 2024, NDVI was 0.220, remaining close to the maximum value over the observation period (Fig. 8). The average annual NDVI growth during 2016–2021 was 0.0122, indicating a stable and intensive regeneration phase. EVI demonstrated even more active recovery, with an average annual increase of 0.0379 during the same period. SAVI concurrently reflected the recovery of herbaceous and shrub formations, particularly in sparsely vegetated areas. The NBR index recorded a peak burn in 2006 and gradual recovery in the following years. BSI spiked immediately after the fire, indicating exposed soil, and gradually declined as the protective surface layer reformed (Fig. 8). Overall, vegetation recovery at the Alksnynė site following the 2006 fire can be described as rapid and effective, with the highest regeneration rates occurring during 2016–2021. Spectral index data confirm a consistent trend and productivity levels comparable to or exceeding pre-fire conditions (Fig. 9).

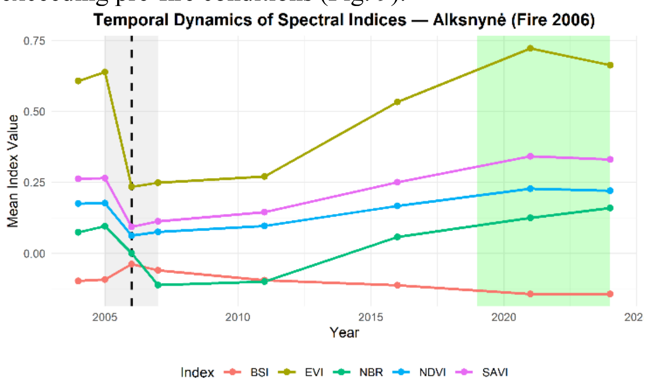

Fig. 8 Long-term dynamics of average spectral index values at the Alksnynė site affected by fire within the Curonian Spit. The grey background with a dashed line indicates the fire event, while the green background highlights the period of stable vegetation recovery. Numerical values used to construct the time series are provided in Table S3 (Supplementary Material)

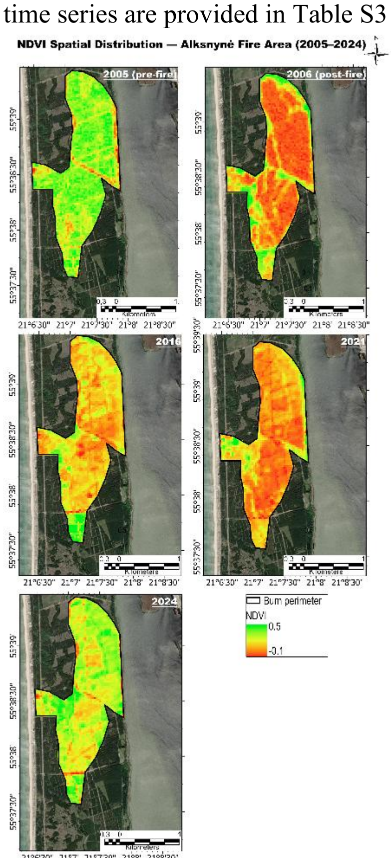

Fig. 9 Spatial distribution of NDVI at various stages of restoration in the Alksnynė area affected by fire within the Curonian Spit

Juodkrantė Site. The long-term analysis of spectral indices at the Juodkrantė site revealed significant changes in vegetation characteristics in response to the fire (Fig. 10). Before the fire, the average NDVI value was 0.232, corresponding to a high level of vegetation productivity and density. After the fire, as of late April 2014, NDVI sharply declined to 0.069, reflecting near-complete destruction of vegetation within the affected area (Fig. 10). Recovery processes began within the first year, but the most notable positive dynamics were recorded between 2015 and 2019, when NDVI increased from intermediate levels to 0.142. As of 2024, NDVI reached 0.192, indicating partial recovery of photosynthetically active biomass (Fig. 10). The average annual NDVI increase during the active regeneration phase (2015–2019) was 0.0085, indicating a stable but moderate recovery rate. The EVI index, which is more sensitive to dense vegetation, showed a stronger recovery trend: during 2015–2019, the average annual increase was 0.0333, indicating the regeneration of dense, mature vegetation, particularly in the central part of the site. SAVI and BSI indices confirmed the regeneration of herbaceous and shrub vegetation, as well as the gradual restoration of the soil protective layer. NBR, as an indicator of fire impact, captured the effects of the 2014 wildfire and showed signs of gradual recovery during 2019–2024 (Fig. 10). Vegetation recovery at the Juodkrantė site showed a steady positive trend, although NDVI values had not fully returned to pre-fire levels by 2024 (Fig. 11).

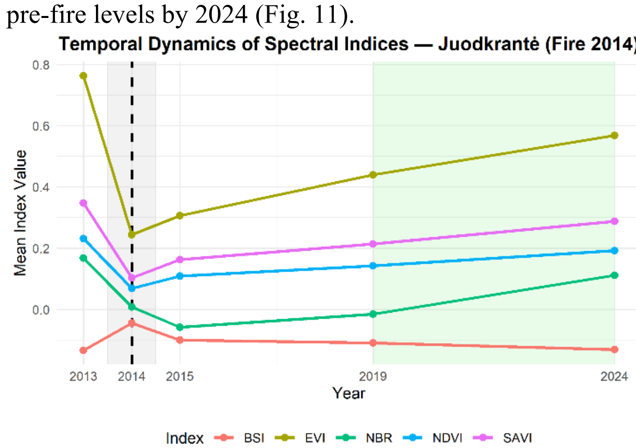

Fig. 10 Long-term dynamics of average spectral index values at the Juodkrantė site affected by fire within the Curonian Spit. The grey background with a dashed line indicates the fire event, while the green background highlights the period of stable vegetation recovery. Numerical values used to construct the time series are provided in Table S4 (Supplementary Material).

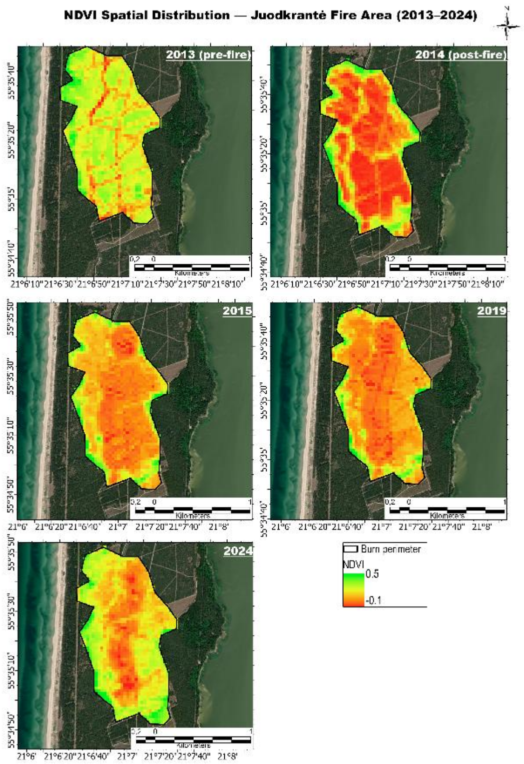

Fig. 11 Spatial distribution of NDVI at various stages of restoration in the Juodkrantė area affected by fire within the Curonian Spit

C. Reference and post-fire vegetation condition: NDVI analysis by percentiles and mean values

While the multi-index approach was applied to track specific recovery mechanisms over time (as detailed in Section IV-B), NDVI was specifically selected as the primary integrated metric for analyzing the statistical distribution (percentiles) of long-term pre- and post-fire vegetation conditions. Using NDVI as the core baseline indicator allows for a robust assessment of overall structural shifts in ecosystem productivity without the redundancy of duplicating multi-decadal percentile calculations for all specialized indices.

To further contextualize the temporal recovery trends, changes in NDVI distribution before and after fire events were analyzed using percentile-based metrics and mean values. The analysis revealed clear differences in vegetation recovery patterns between the Kinburn Peninsula and the Curonian Spit sites. At the Kinburn and Juodkrantė sites, degradation of the most productive formations was observed: a decline in the 90th NDVI percentile (P90) indicates the loss of mature coniferous communities, while a moderate increase in the 10th percentile (P10) reflects the initial recovery of vegetation in sparsely covered areas—primarily through herbaceous and shrub species. Mean NDVI values in these regions also declined, confirming an overall regression in ecosystem productivity.

In contrast, the Smiltynė and Alksnynė sites show signs of stable recovery. Despite a similar narrowing of the NDVI distribution, an increase in mean NDVI values was recorded, which may indicate the development of new, more productive secondary plant communities. Such dynamics may be attributed to favorable climatic conditions, as well as differences in soil composition, vegetation types, and reforestation efforts. Vegetation recovery following wildfires is regionally specific: southern areas are characterized by slower and less complete productivity restoration, while northern sites show more pronounced signs of regeneration, accompanied by an increase in average productivity (Fig. 12).

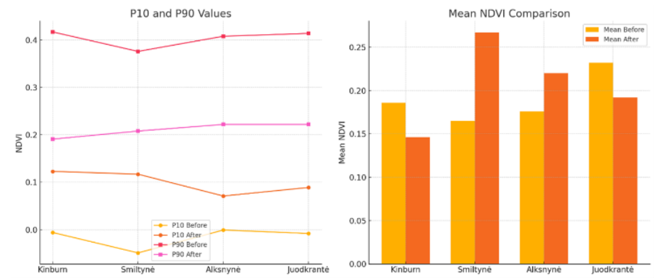

Fig. 12 Changes in vegetation productivity: (a) Comparison of the 10th and 90th percentiles (P10 and P90) of NDVI values before and after wildfires at each study site; (b) Mean NDVI values before and after the fires, illustrating overall changes in ecosystem productivity

The observed shifts in NDVI parameters (P10, P90, and mean values) illustrate the structural changes in vegetation: in the Kinburn and Juodkrantė sites, signs of degradation in high-productivity formations prevail, whereas at Smiltynė and Alksnynė, recovery was more effective and accompanied by an increase in overall productivity.

D. post-fire vegetation recovery: quantitative assessment and indicator relationships

Recovery Rate values were calculated over the period from the fire year to 2024 for each study site.

To assess post-fire vegetation dynamics across the four study sites, two key indicators were calculated: Recovery Rate and Normalized Recovery Index (NRI). These metrics enabled a quantitative characterization of the speed and relative magnitude to which ecosystems returned to their pre-disturbance state based on NDVI. The multi-index normalized recovery values, calculated recovery rates, and detailed interpretations for each site are summarized in Supplementary Table S5.

The analysis revealed distinct differences among the sites:

• Kinburn (Δt = 23 years) showed a moderate recovery rate (0.0012 NDVI/year) and incomplete normalized recovery (NDVI_NRI=0.38), indicating a slow regeneration primarily through less productive communities.

• Smiltynė (Δt = 29 years) had a moderate recovery rate (0.0060 NDVI/year), yet by 2024, NDVI had exceeded pre-fire values (NDVI_NRI=1.46). This indicates that vegetation productivity has stabilized at levels exceeding pre-fire conditions.

• Alksnynė (Δt = 18 years) was characterized by a strong recovery rate (0.0088 NDVI/year) and and high normalized recovery (NDVI_NR = 1.39), reflecting robust regeneration with increased vegetation productivity.

• Juodkrantė (Δt = 10 years) exhibited the highest recovery rate (0.0123 NDVI/year), but did not reach pre-fire NDVI levels (NDVI_NR = 0.75).

An exploratory correlation analysis between the recovery rate and normalized recovery NDVI_NR revealed a weak, non-significant linear relationship (Pearson's correlation coefficient r = 0.34, p=0.656). This lack of statistical significance is expected given the small sample size (n = 4). However, within the context of our analyzed dataset, this confirms a critical ecological insight: a high NDVI growth rate does not necessarily guarantee the ecosystem's full return to its original state. The visual interpretation is presented in Fig. 13:

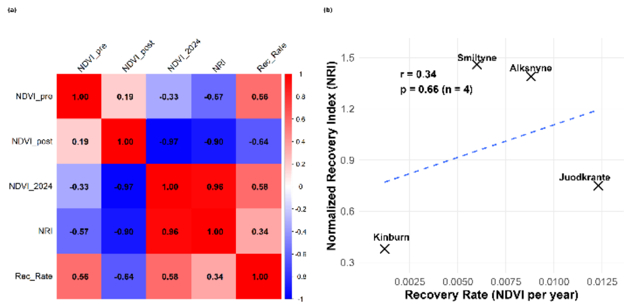

Fig. 13 Relationship between NDVI Recovery Rate and Normalized Recovery: (a) Relationship between recovery rate and normalized recovery based on NDVI for the four study sites. The lack of a direct linear relationship illustrates that a higher rate of recovery does not necessarily imply a full return of the ecosystem to its pre-disturbance condition. (b) Correlation matrix showing the relationships between NDVI values at different time points (pre-fire, fire year, and 2024), along with the calculated recovery indicators. The weak, non-significant correlation between Recovery Rate and Normalized Recovery (r = 0.34) underscores the discrepancy between growth rate and actual recovery magnitude.

V. Discussion

The analysis of satellite data showed that vegetation recovery dynamics in sandy coastal landforms after wildfires depend on climatic conditions, vegetation type, topography, and disturbance regime. In this context, the comparison between the Curonian Spit and the Kinburn Peninsula revealed pronounced differences in both the pace of spectral recovery and the trajectories inferred from vegetation indices.

Sites located on the Curonian Spit, particularly Smiltyne and Alksnynė, demonstrated a high degree of NDVI recovery, reaching or exceeding pre-fire levels, which indicates increased spectral productivity of post-fire vegetation cover. Contributing factors include a favorable thermal regime, sufficient precipitation and humidity, and the original composition of forest vegetation.

In contrast, the Kinburn and the Juodkrantė site showed only partial spectral recovery within the analyzed period. In the case of Kinburn, this was influenced by arid conditions (up to 400 mm of annual precipitation) and the natural zonation, represented by psammophytic steppe vegetation limit post-fire recovery of tree-dominated communities [48]. Under such conditions, the recovery of artificial forests cannot proceed naturally and must be supported by silvicultural interventions. Within the fire-affected areas of the Kinburn Peninsula, vegetation recovery exhibited a mixed character, combining artificial reforestation efforts with natural succession. Specifically, out of the approximately 1600 ha affected by the 2001 fire, artificial pine plantations were established over 870 ha, whereas natural regeneration of forest stands was recorded on only 10 ha. The remaining territory is currently dominated by herbaceous sandy vegetation. The effectiveness of these artificial restoration measures proved to be extremely limited: out of the 870 ha planted, only a small fraction of the saplings successfully took root and established, while the vast majority desiccated and died due to severe moisture deficits and burial by reactivated aeolian sand deposits.

Recent declines in vegetation index values observed after 2022 may reflect renewed disturbance events; however, the available satellite data do not allow unambiguous attribution to specific drivers without independent disturbance inventories or field verification

At the Juodkrantė site, partial recovery is primarily related to the relatively short time elapsed since the fire event. Over the approximately ten-year post-fire period, vegetation indices have not yet returned to pre-fire levels, indicating that the recovery process remains ongoing.

On the Curonian Spit, recovery progressed more rapidly than on the Kinburn Peninsula, reflecting differences in environmental support and disturbance history. These contrasting patterns highlight that recovery trajectories in sandy coastal systems are strongly site-specific and cannot be generalized across regions with differing climatic and land-use contexts [44].

An important trend identified in the study is that a high Recovery Rate does not necessarily correlate with Normalized Recovery. For instance, Juodkrantė had the highest NDVI growth rate, yet it did not reach pre-fire levels. This result supports the interpretation that rapid post-fire increases in vegetation indices may reflect early successional stages rather than full restoration of pre-fire vegetation structure.

It is important to distinguish between post-fire vegetation recovery and ecosystem resilience. While recovery metrics derived from vegetation indices describe the rate and magnitude of spectral response, they do not necessarily reflect the restoration of pre-fire vegetation structure, species composition, or long-term ecosystem stability [18], [41]. Previous studies have shown that rapid post-fire increases in NDVI may correspond to early successional or opportunistic vegetation types, including the rapid regeneration of herbaceous steppe flora, rather than resilient forest ecosystems [7], [15], [40]. Therefore, recovery rate should not be interpreted as a direct proxy for ecosystem resilience, particularly under contrasting climatic conditions and disturbance regimes [23], [38].

The integrated use of multiple vegetation indices enabled more comprehensive characterization of post-fire dynamics than any single index alone. This approach proved particularly useful in sandy and aeolian environments, where high substrate reflectance and sparse vegetation cover can distort individual spectral indicators.

Our findings are crucial for understanding possible future scenarios of vegetation recovery on sandy coastal surfaces. In particular, it is important to consider the impact of climatic differences on this process. In less humid regions, repeated fires pose a real threat of complete ecosystem loss, potentially leading to irreversible changes and the formation of desert or semi-desert areas instead of forested landscapes [12], [23], [24], [25].

Thus, the success of ecosystem recovery is determined by the combined influence of climatic, biophysical, and anthropogenic factors. The results highlight the need for adapted land-use and reforestation strategies, based on spatiotemporal monitoring [35].

Satellite-based observations should ideally be complemented by field-based measurements to improve interpretation and validation of spectral recovery signals. At present, field research is only possible in the affected areas of the Curonian Spit (Lithuanian part). In April 2025, initial fieldwork was conducted to study and assess the condition of the spit's vegetation cover, and sandy soil samples were taken to determine the humus content in the soil in areas affected by fires at different times (Fig. 14). These data will enable future integration of satellite-derived recovery trends with soil and vegetation processes occurring after fire disturbance.

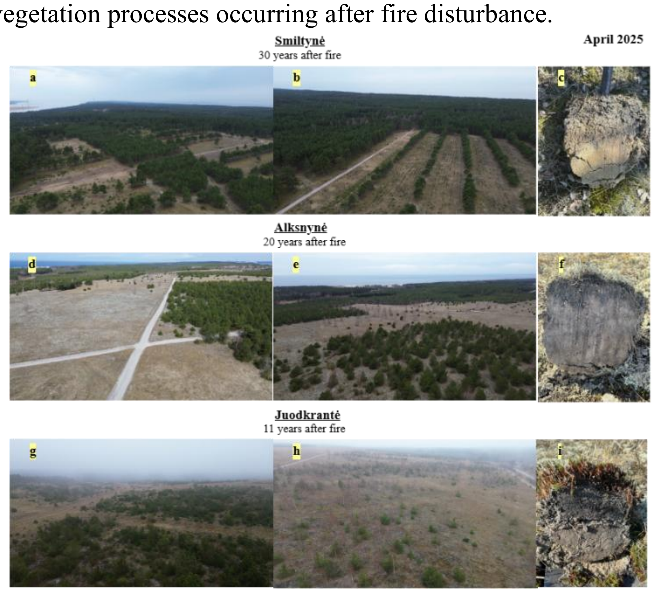

Fig. 14. Current state of vegetation cover and soil sampling at the fire-affected sites on the Curonian Spit: Smiltynė (a-c), Alksnynė (d-f), and Juodkrantė (g-i). Photographed during the initial fieldwork in April 2025.

VI. Conclusions

This study, based on the analysis of multi-year satellite data and multi-indicator spectral approach, evaluated post-fire vegetation recovery across geomorphologically comparable but climatically contrasting sandy landforms.[48]. The findings led to the following generalized conclusions:

1. Environmental and climatic constraints govern recovery trajectories: The natural and climatic regime, combined with the physical properties of the sandy substrate, plays a determinant role in post-fire regeneration. More humid conditions support robust and complete spectral recovery of forested landscapes, whereas arid climates render these ecosystems highly vulnerable to degradation, severely limiting natural succession and requiring constant silvicultural interventions.
2. Robustness of the multi-indicator approach: The integration of multiple spectral indices (NDVI, EVI, SAVI, NBR, BSI) effectively mitigates the distortions caused by high soil reflectance and sparse vegetation cover typical of sandy environments. This provides a reproducible and reliable methodology for monitoring various vegetation types and post-fire successional stages.
3. Importance of robust pre-fire baselines: Utilizing a 20-year retrospective dataset to derive median pre-fire NDVI values provides an objective, long-term baseline. This approach successfully underpins the calculation of normalized spectral recovery, serving as a reliable relative indicator of the ecosystem's actual return to its pre-disturbance state.
4. Site-specificity of ecosystem regeneration: Post-fire vegetation recovery is highly site-specific. The observed outcomes—ranging from incomplete regeneration to productivity exceeding pre-fire levels—reflect a complex interplay of the time elapsed since the fire, local disturbance histories, and specific successional pathways rather than a simple time-dependent recovery process.
5. Discrepancy between recovery rate and actual magnitude: An exploratory correlation analysis between the recovery rate and normalized recovery revealed a weak, non-significant linear relationship ($r = 0.34$). This highlights a critical ecological insight: rapid initial post-fire index growth often reflects the quick establishment of early successional species rather than the attainment of full pre-fire ecosystem characteristics, emphasizing that ecosystem recovery cannot be evaluated solely based on growth rate metrics.

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His recent output bridges methods and applications: a machine-learning study on river-ice detection and automated classification (2023); a Curonian Spit case study comparing UAV photogrammetry with ground measurements (2019); an article on cartographic functional styles for wind-energy mapping in Advances in Geodesy and Geoinformation (2025). These works reflect a consistent focus on EO data (Landsat/Sentinel), UAV workflows, and cartographic design for environmental decision-making.