

Wildfire Dynamics on the Kinburn Peninsula, Ukraine, Using Sentinel-1 SAR and Optical Data (2022–2025)

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Abstract

Since 2022, the Kinburn Peninsula, Ukraine, has been located within an active war zone, where frequent and recurrent wildfires have affected heterogeneous coastal sandy ecosystems. Burned-area mapping in this landscape is complicated by wetlands, salt flats, exposed sands, reedbeds, artificial pine plantations, cloud cover, smoke and restricted field access. This study applies an integrated multi-sensor approach to map wildfire damage and recurrence during 2022–2025 using Sentinel-1 SAR, Sentinel-2 and Landsat 8/9 optical imagery, NASA FIRMS thermal anomalies and official fire-monitoring materials. Optical burn indicators were used to identify spectral evidence of burning, while Sentinel-1 VV/VH backscatter changes and Radar Forest Degradation Index (RFDI) were used to detect structural vegetation degradation. Optical burn candidate masks and SAR-derived structural damage masks were spatially overlaid to delineate confirmed fire-damage areas. The results show that wildfire impact was spatially recurrent rather than isolated. SAR-derived candidate areas increased from 637.06 ha in 2022 to 4297.97 ha in 2025, while mean ΔVH remained consistently negative, indicating reduced vegetation volume scattering. The largest confirmed optical–SAR fire-damage area was detected in 2025, reaching 598.26 ha. Fire recurrence mapping revealed zones of accumulated pyrogenic stress, particularly within artificial forest plantations, psammophytic steppe complexes and protected coastal ecosystems. The proposed optical–SAR framework improves wildfire damage mapping under wartime and data-limited conditions.

1. Introduction

Wildfires are among the major drivers of vegetation transformation in dry coastal and sandy landscapes (Bond and Keeley, 2005; Keeley et al., 2011). In such environments, fire affects not only above-ground biomass and vegetation structure, but also sand stabilization, soil fertility, habitat dynamics, and ecosystem resilience to subsequent disturbances. Recurrent fires are particularly damaging because they may interrupt post-fire recovery and promote cumulative degradation of vegetation cover, especially in fragile sandy ecosystems (Keeley et al., 2011; Ermitão et al., 2024).

The Kinburn Peninsula, located in southern Ukraine between the Dniprovsko–Buzkyi Liman, Yavorlytskyi Bay, and the Black Sea, represents a highly heterogeneous coastal landscape composed of weakly consolidated sandy deposits, psammophytic steppe communities, wetlands, floodplain meadows, coastal salt flats, reedbeds, natural shrub vegetation, and planted pine forests (Shevchuk et al., 2026).

The area has high conservation value and includes several protected territories, such as the Black Sea Biosphere Reserve, the Biloberezhzhia Sviatoslava National Nature Park, and the Kinburn Spit Regional Landscape Park (Petrenko et al., 2025).

Since 2022, the Kinburn Peninsula has been located within an active war zone, which has been associated with frequent wildfire occurrence and the formation of a recurrent fire regime. Fires have repeatedly affected the same locations, creating a complex mosaic of single, double, and multiple burn events (Kasianov, 2025).

Under these conditions, the conventional “pre-fire–post-fire” approach is insufficient, because the same area may be burned several times within one season or across different years. Restricted field access, smoke, cloud cover, and the impossibility of systematic ground validation further complicate reliable burned-area mapping.

Remote sensing is therefore the primary tool for monitoring fire damage in this region (Chuvieco et al., 2019). Optical data from Sentinel-2 and Landsat 8/9 allow the assessment of vegetation loss and burn severity using spectral indices such as the Normalized Difference Vegetation Index (NDVI), Normalized Burn Ratio (NBR), and differenced Normalized Burn Ratio (dNBR) (Key and Benson, 2006; Miller and Thode, 2007).

However, optical fire mapping is limited by cloud cover, smoke, seasonal vegetation dynamics, and the spectral similarity between burned areas, wet sand, exposed sandy surfaces, shallow water, and salt flats (Veraverbeke et al., 2012; Chuvieco et al., 2019). In this context, Sentinel-1 SAR data provide an important complementary source of information, as radar backscatter is sensitive to vegetation structure, surface moisture, and roughness and can be acquired independently of cloud cover and solar illumination (Tanase et al., 2010; Belenguer-Plomer et al., 2019; Ban et al., 2020).

This study aims to assess the spatio-temporal dynamics of wildfire damage on the Kinburn Peninsula during 2022–2025 by integrating Sentinel-1 SAR data, Sentinel-2 and Landsat optical indicators, NASA FIRMS thermal anomalies and official fire-monitoring materials (Giglio et al., 2016; Kasianov, 2023; Kasianov, 2025; Petrenko et al., 2025). In this study, “fire dynamics” refers to the spatial distribution, annual extent,

recurrence and satellite-detected severity of wildfire damage, rather than to fire behaviour or combustion processes.

Particular attention is given to recurrent fires, structural vegetation degradation and the identification of areas where optical burn evidence is confirmed by radar-derived structural damage. The novelty of this study lies not in the individual use of optical or SAR indicators, but in their integration for mapping recurrent fire damage in a field-inaccessible, conflict-affected coastal sandy landscape.

The specific objectives were to:

- (1) generate annual fire-damage layers for 2022–2025 using optical and SAR data;
- (2) calculate optical and SAR indicators used for candidate fire-damage mapping;
- (3) compare optical and radar-derived damage patterns to delineate confirmed fire-damage areas;
- (4) map fire recurrence and assess the distribution of damaged areas within protected coastal ecosystems.

This multi-sensor approach is designed to improve fire-damage mapping under conditions of recurrent burning, limited optical data quality and restricted field access, providing a basis for assessing accumulated pyrogenic stress in coastal sandy ecosystems.

2. Study Area

The study area covers the Kinburn Peninsula, located in southern Ukraine between the Dniro–Bug Estuary, Yavorlyk Bay and the Black Sea. The peninsula forms part of the north-western Black Sea coastal zone and represents a complex sandy coastal landscape characterized by high geomorphological and ecological heterogeneity. The analysis area also includes adjacent sandy and wetland complexes affected by wildfire activity during 2022–2025. The location of the study area and protected-area boundaries are shown in Figure 1.

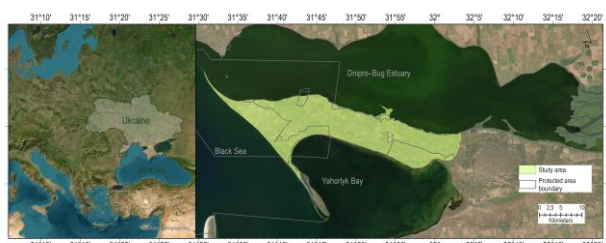


Figure 1. Location of the Kinburn Peninsula study area and protected-area boundaries within the north-western Black Sea coastal region.

The territory is composed mainly of sandy deposits and is located within an arid steppe environment, where low precipitation and high summer temperatures create favourable conditions for fire occurrence and spread.

The landscape includes weakly consolidated sandy massifs, psammophytic steppe vegetation, meadow and wetland complexes, reedbeds, coastal salt flats, open sandy surfaces, natural shrub vegetation and artificial pine plantations. This fine-scale mosaic of vegetation and surface types complicates

burned-area delineation because different ecosystems may show contrasting optical and radar responses to fire disturbance.

The Kinburn Peninsula has high conservation value. Large parts of the territory are included in protected areas, including the Biloberezhzhia Sviatoslava National Nature Park, the Kinburn Spit Regional Landscape Park and sections of the Black Sea Biosphere Reserve (Petrenko et al., 2025). These protected areas contain coastal sandy ecosystems, wetland habitats, psammophytic plant communities and planted forest stands that play an important role in stabilizing sandy surfaces.

Since 2022, the peninsula has been located within an active war zone, where restricted access, absence fire suppression capacity and repeated ignition sources have contributed to recurrent wildfire activity (Kasianov, 2023; Kasianov, 2025). As a result, the study area provides a relevant case for analysing recurrent wildfire damage in coastal sandy ecosystems under conditions of limited field validation and complex remote-sensing interpretation.

For spatial analysis, the study area was defined to include the Kinburn Peninsula and adjacent fire-affected territories within the southern sector of the Lower Dniro sandy arenas. The approximate geographic extent ranges from 31.5014°E, 46.5841°N to 32.2739°E, 46.3571°N, corresponding to the area used in official fire monitoring and subsequent satellite-based analysis.

3. Materials and Methods

3.1 Data Sources

This study used a multi-sensor dataset covering the period from 2022 to 2025. The main data sources included Sentinel-1 SAR, Sentinel-2 MSI, Landsat 8/9 OLI/TIRS, NASA FIRMS thermal anomalies, and official fire monitoring materials provided by the Biloberezhzhia Sviatoslava National Nature Park.

Sentinel-1 GRD data in VV and VH polarizations were used to assess radar backscatter changes and structural vegetation damage. Sentinel-2 Level-2A and Landsat 8/9 surface reflectance data were used to calculate optical fire and vegetation indices, including NDVI, NBR and dNBR.

NASA FIRMS thermal anomaly data were used to identify active fire phases and support the temporal interpretation of fire events. Official fire monitoring data and burned-area maps were used as reference information for interpreting fire chronology and validating mapped fire-damage patterns.

Table 1. Main datasets used for wildfire damage mapping and recurrence analysis.

Dataset	Period	Main use
Sentinel-1 GRD VV/VH	2022–2025	SAR backscatter change and structural vegetation damage
Sentinel-2 L2A	2022–2025	Optical fire indicators: NDVI, NBR, dNBR, NIDICG, dBAIS2
Landsat 8/9 OLI/TIRS	2022–2025	SWIR composites and optical vegetation/burn indicators
NASA FIRMS	2022–2025	Active fire detection and fire chronology
Official fire monitoring data	2022–2025	Reference fire perimeters, fire chronology and recurrence analysis

3.2 Pre-processing and Water Masking

All satellite data were processed in Google Earth Engine (Gorelick et al., 2017). Sentinel-2 images were filtered by cloud cover and masked using the Scene Classification Layer. Landsat 8/9 surface reflectance data were masked using the Quality Assessment Pixel (QA_PIXEL) band and converted to reflectance values using Collection 2 Level-2 scale factors.

Because the Kinburn Peninsula contains extensive wetlands, shallow water, wet sand, salt flats and coastal transition zones, water masking was performed conservatively. Only confident open water was removed from the analysis.

A combined water mask was created using the Joint Research Centre (JRC) Global Surface Water dataset (Pekel et al., 2016) and annual Modified Normalized Difference Water Index (MNDWI) based masks derived from Sentinel-2 and Landsat imagery (Xu, 2006). Stable open water was excluded, whereas wet sand, salt flats, wetlands, dry lake bottoms and burned coastal transition zones were retained for analysis.

3.3 Optical Fire Indicators

Optical analysis was based on pre-fire and post-fire composites for each year from 2022 to 2025. Sentinel-2 and Landsat 8/9 images were used to calculate vegetation and burn indices: the Normalized Difference Vegetation Index (NDVI), Normalized Burn Ratio (NBR), differenced Normalized Burn Ratio (dNBR), Near-Infrared Dimming Index with Green normalization (NIDICG), and differenced Burned Area Index for Sentinel-2 (dBAIS2) were used to identify optical evidence of burning and vegetation damage.

NBR and dNBR were used as standard burn-severity indicators (Key and Benson, 2006; Miller and Thode, 2007), while dBAIS2 was included as an additional Sentinel-2 burned-area indicator (Filipponi, 2018). Optical burn candidates were defined using the combined threshold criteria shown in Table 2.

The difference in BAIS2 was used as an additional burned-area indicator for Sentinel-2 imagery. Optical burn candidate masks were generated using the combined response of dNBR, NIDICG and dBAIS2 and were further checked using SWIR composites and FIRMS thermal anomalies.

3.4 Sentinel-1 SAR Indicators

Sentinel-1 SAR data were used to assess structural changes in vegetation cover. For each year, pre-fire and post-fire SAR composites were created using VV and VH polarizations. Sentinel-1 VV and VH backscatter changes were used to detect structural vegetation degradation.

RFDI was calculated using VV and VH values converted from dB to linear scale. SAR candidates were defined by strong VH decrease and positive dRFDI values. Positive dRFDI values were interpreted as an increase in radar-based degradation signal (Tanase et al., 2010; Belenguer-Plomer et al., 2019; Ban et al., 2020).

SAR burn candidate masks were generated using the combined condition of strong VH decrease and positive dRFDI. These masks were interpreted as areas of potential structural vegetation damage (Table 2).

3.5 Optical-SAR Integration

Optical and SAR-derived fire indicators were integrated using a spatial overlay approach. For each year, pre-fire and post-fire optical and SAR composites were defined according to the timing of fire activity identified from FIRMS thermal anomalies and official monitoring materials.

Where repeated fires occurred, annual post-fire composites represented cumulative fire-related damage within the available cloud-free observation window. Optical burn candidate masks were used to identify areas with spectral evidence of fire damage, while SAR burn candidate masks were used to identify areas with structural vegetation damage. Areas where both masks overlapped were classified as confirmed fire-damage zones. Confirmed fire damage was defined as the spatial overlap between optical burn candidates and SAR-derived structural damage candidates.

This approach allowed the separation of three types of fire-related signals: optically detected burn damage, SAR-derived structural disturbance, and confirmed damage where both optical and radar indicators agreed.

Table 2. Optical and SAR indicators and threshold criteria used for fire-damage candidate mapping.

Indicator layer	Formula or criterion	Interpretation
NDVI	$(\text{NIR} - \text{Red}) / (\text{NIR} + \text{Red})$	Vegetation greenness and post-fire vegetation change
NBR	$(\text{NIR} - \text{SWIR2}) / (\text{NIR} + \text{SWIR2})$	Vegetation moisture and burn-related spectral response
dNBR	$\text{NBR}_{\text{pre}} - \text{NBR}_{\text{post}}$	Burn severity indicator
NIDICG	$(\text{NIR}_{\text{pre}} - \text{NIR}_{\text{post}}) / \text{Green}_{\text{post}}$	Post-fire decrease in NIR reflectance
dBAIS2	$\text{BAIS2}_{\text{post}} - \text{BAIS2}_{\text{pre}}$	Burned-surface spectral response
$\Delta\text{VV}, \Delta\text{VH}$	$\sigma^0_{\text{post}} - \sigma^0_{\text{pre}}$	Radar backscatter change after fire disturbance
RFDI	$(\text{VV} - \text{VH}) / (\text{VV} + \text{VH})$	Radar-based vegetation degradation index
dRFDI	$\text{RFDI}_{\text{post}} - \text{RFDI}_{\text{pre}}$	Increase in radar-based degradation signal
Optical candidate	$\text{dNBR} \geq 0.27; \text{NIDICG} > 0; \text{dBAIS2} > 0$	Spectrally detected fire damage
SAR candidate	$\Delta\text{VH} \leq -1.5 \text{ dB}; \text{dRFDI} > 0$	Radar-detected structural damage
Confirmed fire damage	$\text{Optical candidate} \cap \text{SAR candidate}$	Highest-confidence fire-damage class

The dNBR threshold of 0.27 was selected to represent moderate-to-high optical fire damage, while $\Delta\text{VH} \leq -1.5 \text{ dB}$ was used to identify strong decreases in vegetation volume scattering. These thresholds were adjusted to the heterogeneous sandy and wetland conditions of the Kinburn Peninsula through visual comparison with SWIR composites, FIRMS thermal anomalies and official fire-monitoring materials.

3.6 Fire Recurrence and Area Statistics

Annual confirmed fire-damage layers were created for 2022, 2023, 2024 and 2025. Fire recurrence was assessed by summing the annual binary confirmed fire-damage masks. The resulting recurrence map identified areas affected once, twice, or three or more times during the study period. These recurrence classes were used to identify zones of accumulated pyrogenic stress.

Area statistics were calculated in ArcGIS Pro. Confirmed fire-damage masks were converted to polygon format, cleaned to remove small isolated patches, dissolved by year, and intersected with protected-area boundaries. This allowed the calculation of annual confirmed fire-damage area, recurrence classes, and the distribution of damaged areas within the main protected-area units of the Kinburn Peninsula.

3.7 Reliability and Limitations

The reliability of fire-damage mapping was evaluated using a multi-source confirmation approach. High-confidence fire-damage areas were defined as those supported by several independent indicators, including FIRMS thermal anomalies, SWIR interpretation, optical index response, official fire-monitoring materials and Sentinel-1 SAR-derived structural change. Lower confidence was assigned to small, recurrent, partially obscured or spectrally ambiguous burn scars.

The main interpretation uncertainties were related to cloud cover, smoke, repeated fires over old burn scars, low-intensity fires beneath canopy, wet sand, shallow water, shoreline dynamics, seasonal vegetation variability and time gaps between valid satellite observations. SAR backscatter may also be affected by soil moisture, surface roughness, incidence angle and vegetation structure.

Therefore, SAR indicators were interpreted only as part of an integrated optical–radar framework. Because systematic field validation was not possible under wartime conditions, the results represent satellite-based estimates of fire damage rather than field-validated burn perimeters. The highest confidence was assigned to areas where optical and SAR evidence overlapped (Olofsson et al., 2014).

4. Results

4.1 Annual fire-damage patterns

Annual confirmed fire-damage maps showed that wildfire impact on the Kinburn Peninsula during 2022–2025 was spatially heterogeneous and highly variable between years (Figure 2).

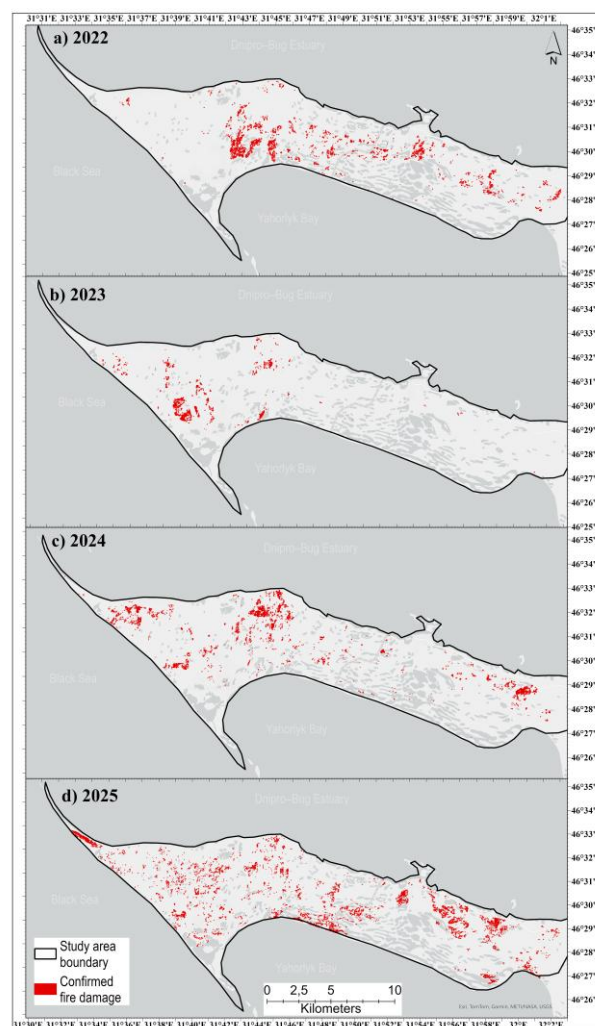


Figure 2. Annual distribution of confirmed fire-damage areas on the Kinburn Peninsula during 2022–2025.

The confirmed fire-damage areas were not evenly distributed across the peninsula, but formed clusters within forest plantations, psammophytic steppe complexes, wetland margins and protected coastal ecosystems.

The confirmed optical–SAR fire-damage area reached 366.10 ha in 2022, decreased to 153.08 ha in 2023, increased again to 357.70 ha in 2024, and reached its maximum of 598.26 ha in 2025. This pattern indicates that wildfire damage was not a single isolated event, but a recurrent and spatially shifting disturbance process affecting different sectors of the peninsula over the study period.

4.2 Sentinel-1 SAR response to fire damage

Sentinel-1 SAR data showed a consistent response to fire-related vegetation disturbance (Figure 3). The most stable signal was observed in VH polarization, which is sensitive to volume scattering within vegetation. Mean ΔVH values were negative in all years, ranging from -2.954 dB in 2022 to -3.701 dB in 2025. This indicates a persistent decrease in vegetation structural scattering within SAR-derived fire candidate areas.

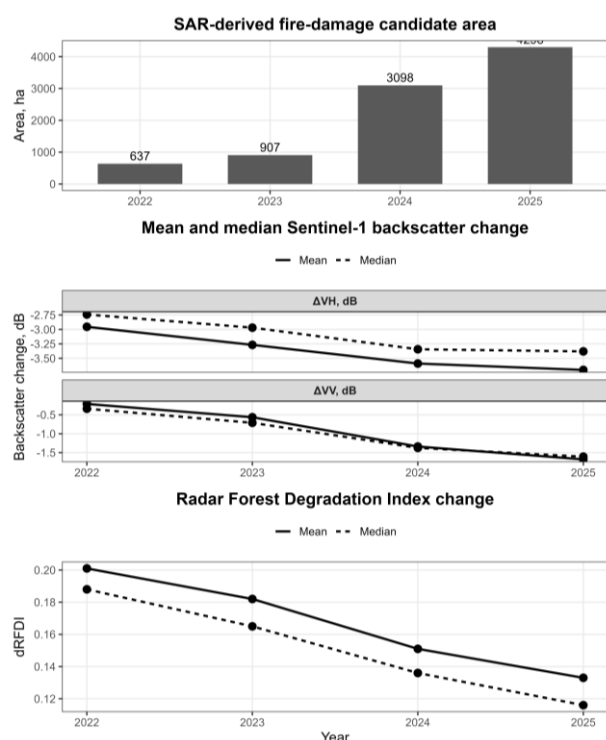


Figure 3. SAR-derived fire-damage candidate area and Sentinel-1 radar indicator changes on the Kinburn Peninsula during 2022–2025.

Mean ΔVV also became progressively more negative, decreasing from -0.212 dB in 2022 to -1.678 dB in 2025. Although the VV response was weaker and more heterogeneous than VH, its gradual decline supports the interpretation of increasing surface and structural disturbance. Positive mean dRFDI values in all years further indicate radar-detected vegetation degradation within the SAR candidate masks.

The SAR-derived candidate area increased from 637.06 ha in 2022 to 4297.97 ha in 2025, suggesting a substantial expansion of areas with radar-detected structural vegetation disturbance. However, SAR candidate areas were larger than confirmed fire-damage areas, indicating that radar backscatter changes may also include non-fire structural or moisture-related disturbances. Therefore, only areas overlapping with optical burn evidence were interpreted as confirmed fire damage.

4.3 Optical–SAR agreement and confirmed fire damage

The spatial overlay of optical burn candidate masks and SAR-derived structural damage masks allowed the delineation of confirmed fire-damage areas. Optical candidate areas represented locations with spectral evidence of burning and vegetation loss, while SAR candidate areas represented zones of radar-detected structural disturbance. Confirmed fire-damage areas therefore indicate locations where both optical and radar evidence agreed.

The confirmed optical–SAR fire-damage area reached 366.10 ha in 2022, 153.08 ha in 2023, 357.70 ha in 2024 and 598.26 ha in 2025 (Figure 4). The highest confirmed fire-damage extent in 2025 indicates the strongest agreement between optical burn evidence and SAR-derived structural disturbance during the study period.

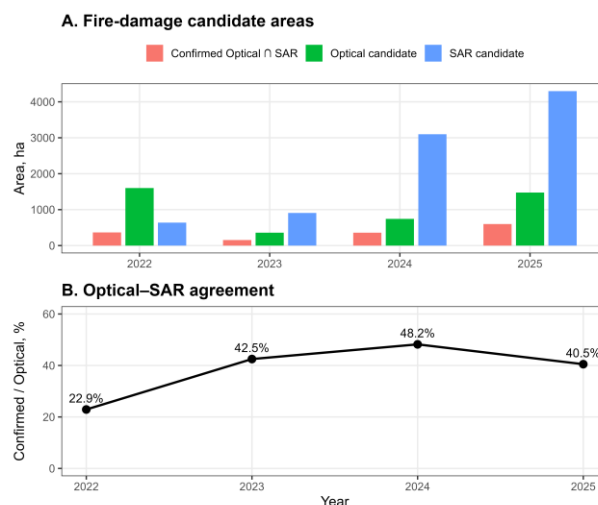


Figure 4. Optical, SAR-derived and confirmed optical–SAR fire-damage candidate areas on the Kinburn Peninsula during 2022–2025.

Confirmed areas represent the spatial overlap between optical burn candidates and SAR-derived structural damage candidates.

The confirmed fire-damage layer reduces uncertainty compared with optical-only or SAR-only mapping. Optical-only areas may include spectrally ambiguous surfaces such as wet sand, exposed sand or salt flats, while SAR-only areas may reflect structural or moisture-related changes not always visible in optical data. Therefore, areas where both indicators coincide represent the most reliable fire-damage class in this study.

4.4 Fire recurrence and accumulated pyrogenic stress

Fire recurrence mapping revealed areas affected once, twice and three or more times during 2022–2025 (Figure 5). Recurrent burning was spatially clustered rather than randomly distributed, particularly within forest plantations, psammophytic steppe communities and protected coastal ecosystems. This pattern indicates the development of zones of accumulated pyrogenic stress.

In 2022–2023, repeated fires were mainly associated with herbaceous, meadow and wetland vegetation, where rapid biomass regeneration may provide fuel for subsequent fires. Since 2024, recurrent burning increasingly affected artificial forest plantations. In these areas, persistent low post-fire vegetation activity together with strong negative ΔVH values suggests limited recovery of closed vegetation cover and the development of secondary fires over dry residues of previously damaged trees.

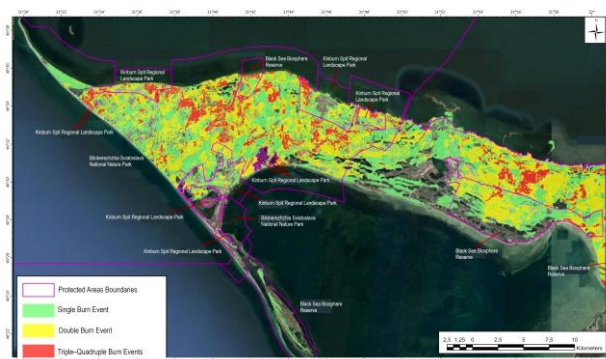


Figure 5. Fire recurrence and accumulated pyrogenic stress across the Kinburn Peninsula during 2022–2025.

4.5 Protected areas and ecological implications

Fire damage affected several protected-area units of the Kinburn Peninsula, including the Biloberezhzhia Sviatoslava National Nature Park, the Kinburn Spit Regional Landscape Park and sections of the Black Sea Biosphere Reserve.

The most vulnerable zones were those where repeated burning coincided with low post-fire vegetation activity and strong SAR-detected structural degradation. The ecological consequences are particularly important for coastal sandy ecosystems, where vegetation plays a key role in stabilizing sandy surfaces and maintaining habitat structure.

Recurrent fires can interrupt post-fire recovery, reduce above-ground biomass, increase exposure of sandy substrates and simplify vegetation structure. Areas with high recurrence, negative ΔVH and positive dRFDI should therefore be considered priority zones for future field validation and post-war conservation planning.

5. Discussion

The results demonstrate that wildfire damage on the Kinburn Peninsula during 2022–2025 should not be interpreted as a sequence of isolated fire events. Instead, the observed pattern reflects a recurrent disturbance regime, in which previously affected areas were repeatedly exposed to new fire episodes. This is particularly important for coastal sandy ecosystems, where vegetation stabilizes sandy surfaces, maintains habitat structure and supports post-fire recovery. Repeated burning may interrupt these recovery processes and increase the risk of long-term vegetation degradation (Keeley et al., 2011; Ermitão et al., 2024; Shevchuk et al., 2026).

The integration of optical and Sentinel-1 SAR data was essential for fire-damage mapping under the complex environmental and wartime conditions of the study area. Optical indices derived from Sentinel-2 and Landsat 8/9 were effective for identifying spectral changes associated with burned surfaces and vegetation loss.

However, optical interpretation was limited by cloud cover, smoke, seasonal vegetation variability and the spectral similarity between burned areas, wet sand, exposed sandy surfaces, salt flats and shallow water (Chuvieco et al., 2019; Veraverbeke et al., 2012). These limitations are especially relevant for the Kinburn Peninsula because of its highly heterogeneous coastal landscape structure.

Sentinel-1 SAR provided complementary information by capturing structural changes in vegetation cover. The consistently negative VH backscatter change within SAR-derived candidate areas indicates a reduction in vegetation volume scattering after fire disturbance. This response is consistent with above-ground biomass loss, canopy damage, drying of vegetation residues and simplification of vegetation structure.

The weaker and more heterogeneous VV response suggests that this polarization was more strongly influenced by surface roughness, soil moisture and exposed sandy or wetland surfaces (Tanase et al., 2010; Belenguer-Plomer et al., 2019; Ban et al.,

2020). Positive dRFDI values further supported the interpretation of radar-detected vegetation degradation.

The spatial overlay between optical burn candidate masks and SAR-derived structural damage masks allowed the identification of confirmed fire-damage areas. These areas represent the most reliable fire-damage class in this study because they combine spectral evidence of burning with radar-detected structural response (Belenguer-Plomer et al., 2019; Chuvieco et al., 2019).

The largest confirmed optical–SAR fire-damage area in 2025 indicates the strongest agreement between surface spectral change and vegetation structural disturbance during the study period. This supports the interpretation that fire impact became more spatially persistent by the end of the analysed period.

Fire recurrence is one of the most ecologically significant findings of this study. Areas affected two or more times can be interpreted as zones of accumulated pyrogenic stress (Keeley et al., 2011; Ermitão et al., 2024). In herbaceous, meadow and wetland communities, rapid regrowth of above-ground biomass may provide fuel for repeated burning.

In artificial pine plantations, repeated fires may develop over dry residues of previously damaged or dead trees, preventing the re-establishment of closed vegetation cover and increasing the risk of long-term degradation (Shevchuk et al., 2026). The combination of recurrent burning, low post-fire vegetation activity, negative VH backscatter change and positive dRFDI values indicates areas where post-fire recovery may be most constrained.

The results also have important implications for protected-area management. Several fire-affected zones are located within or near protected areas of high conservation value, including the Biloberezhzhia Sviatoslava National Nature Park, the Kinburn Spit Regional Landscape Park and sections of the Black Sea Biosphere Reserve (Petrenko et al., 2025).

Repeated fires in these areas may reduce habitat quality, destroy local refugia, simplify vegetation structure and alter future recovery trajectories (Kasianov, 2025). The recurrence map and confirmed fire-damage layers can therefore be used to identify priority areas for future field validation, ecological assessment and post-war restoration planning.

Several limitations should be considered. First, systematic field validation was not possible because the peninsula has been located within an active war zone. Therefore, the results represent satellite-based estimates of fire damage rather than field-verified burn perimeters. Second, both optical and SAR indicators can be affected by non-fire factors.

Optical indices may respond to seasonal vegetation dynamics, surface moisture and exposed sand, while SAR backscatter is influenced by soil moisture, surface roughness, incidence angle and vegetation structure (Olofsson et al., 2014). Third, some mapped fire-damage areas may represent cumulative damage between two valid satellite observations rather than individual fire events. For this reason, the interpretation was based on multi-source agreement between FIRMS thermal anomalies, SWIR composites, optical indices, SAR indicators and official fire-monitoring materials (Giglio et al., 2016).

Overall, the study confirms that combining optical and Sentinel-1 SAR data improves wildfire damage mapping in

heterogeneous coastal landscapes where optical-only approaches are limited. The proposed multi-sensor framework is particularly useful under wartime and data-limited conditions, where field access is restricted and recurrent fire events are difficult to separate temporally.

6. Conclusions

This study demonstrated that wildfire damage on the Kinburn Peninsula during 2022–2025 developed as a recurrent and spatially heterogeneous disturbance process rather than as a set of isolated fire events. The integration of NASA FIRMS thermal anomalies, optical satellite data and Sentinel-1 SAR indicators made it possible to assess fire occurrence, burned-area patterns, structural vegetation damage and fire recurrence under conditions of limited field access.

The combination of optical and radar data improved the reliability of fire-damage interpretation in the complex coastal sandy landscape of the Kinburn Peninsula. Optical indicators derived from Sentinel-2 and Landsat 8/9 were effective for detecting spectral changes associated with burned surfaces and vegetation loss, while Sentinel-1 SAR provided complementary information on structural vegetation degradation. The consistently negative VH backscatter response indicated a reduction in vegetation volume scattering within fire-affected areas.

The largest confirmed optical–radar fire-damage area was detected in 2025, indicating the strongest agreement between spectral burn evidence and radar-derived structural disturbance during the study period. At the same time, the substantial increase in SAR-derived candidate areas from 2022 to 2025 suggests an expansion of structurally disturbed vegetation surfaces.

Fire recurrence mapping revealed zones of accumulated pyrogenic stress, especially within artificial pine plantations, psammophytic steppe communities and protected coastal ecosystems. Repeated burning may interrupt post-fire recovery, reduce vegetation structure, increase exposure of sandy substrates and alter future recovery trajectories.

The proposed multi-sensor framework provides a reliable basis for wildfire damage monitoring in wartime and data-limited conditions. The resulting maps of confirmed fire damage and recurrence can support future field validation, ecological assessment and post-war conservation planning after access to the territory is restored.

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