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Research Article

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# Remote Sensing-Based Multi-Temporal Analysis of Wildfire Impacts in Manavgat, Türkiye (2000-2025)

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**Abstract**

This study provides an integrated, multi-temporal assessment of wildfire dynamics in the Manavgat region (Antalya, Türkiye) between 2000 and 2025 by combining Sentinel-2, Landsat 8/9, MODIS, CORINE/ESA land-cover data, and Sentinel-5P atmospheric observations. The main objective is to quantify long-term vegetation degradation, land-use transitions, fire recurrence patterns, and fire-induced atmospheric anomalies while identifying the topographic and anthropogenic factors that shape fire behaviour. The methodology includes satellite-based spectral index analysis (NDVI, NDMI, and NBR), land-cover classification, topographic modelling (slope and aspect), atmospheric pollutant evaluation (CO and AOD), and spatial overlay of ignition centres with human and geomorphological drivers. Results indicate that wildfire frequency and burned area extent increased sharply after 2008, with 2021 representing an extreme megabore (>75,000 ha). Natural forest cover declined by ~35-40%, while urban and tourism-related land use nearly tripled, particularly along the Çolaklı-Ilıca-Sorgun-Kızılağaç coastal corridor. Fire severity was highest on south- and southwest-facing mid-elevation slopes, where prolonged drought and wind corridors accelerated fuel drying. Sentinel-5P data demonstrated substantial increases in CO and aerosol optical depth during major fire years, confirming significant atmospheric degradation. Post-fire recovery remained weak in most areas, with persistent NDVI/NDMI deficits and slow regeneration, except on shaded, north-facing slopes. This study contributes to the Mediterranean wildfire literature by presenting a unified, multi-source geospatial framework that simultaneously evaluates vegetation loss, land-use fragmentation, topographic control, and atmospheric impacts. Findings highlight that Manavgat has transitioned into a structurally fire-prone landscape, emphasising the need for proactive, data-driven fire management, sustainable spatial planning, and restoration strategies.

**Keywords** Wildfire Analysis · Remote Sensing · Land Cover Change

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## INTRODUCTION

Wildfires are escalating global hazards that profoundly affect ecosystems, human health, and economies, especially in Mediterranean-type environments characterised by dry summers, flammable vegetation, and extensive human influence (Catry et al., 2008; Pausas and Keeley, 2019; FAO, 2020; Moreira et al., 2020; Ersöz, 2023). Although global wildfire studies have primarily focused on Mediterranean-type ecosystems, recent research conducted in Türkiye has begun to reveal the region's distinctive fire dynamics. Several studies have examined wildfire danger mapping, meteorological early warning systems, and the socio-environmental dimensions of the 2021 Manavgat megabore. For instance, Atalay, Dervişoğlu, and Sunar (2024a-b) developed detailed fire danger maps for Antalya and Manavgat forests using meteorological indices, while Çamalan et al. (2023) evaluated the Manavgat fire through the Meteorological Early Warning System (MEUS). Ekberzade et al. (2025) emphasised the human factors and land-use pressures behind megafires in Mediterranean Türkiye, and Kolukırık et al. (2022) analysed societal perceptions and media coverage of the 2021 Manavgat wildfire. Earlier, Sabancı (2016) identified the topographic, climatic, and anthropogenic drivers of forest fires in the Akseki-Gündoğmuş-Manavgat (Karpuz River Basin) region, stressing the combined impacts of drought, tourism activities, and lightning-induced ignition. Collectively, these Türkiye-based investigations provide valuable regional insights that complement global Mediterranean fire studies and highlight the need for locally tailored, data-driven fire management strategies.

In Türkiye's Mediterranean region—particularly the provinces of Antalya, Muğla, and Mersin—the frequency, duration, and spatial extent of wildfires have increased markedly since the early 2000s. Rising temperatures, low relative humidity, and prolonged drought periods are the primary climatic drivers of this trend (Sabancı, 2012; 2016), while human pressures further intensify fire risk. During the summer of 2021, more than 130 forest fires occurred nationwide, burning approximately 75,000 hectares. This pattern is consistent with global wildfire regimes observed in other high-risk Mediterranean environments (Turco et al., 2016; Moreira et al., 2020; Ganteaume et al., 2021). Within this broader context, the July-August 2021 Manavgat megafire in Antalya stands out as one of the most severe events, burning over 75,000 ha and heavily impacting forest, agricultural, and urban landscapes while releasing substantial amounts of aerosols and trace gases into the atmosphere (AFAD, 2021; MGM, 2021; OGM, 2022; Acar & Gönençgil, 2023). Historically, Mediterranean forest ecosystems dominated by *Pinus brutia*, sclerophyllous shrubs, and maquis have been prone to frequent fire regimes (San Miguel Ayanz et al., 2021; Şahan et al., 2023). Climatic drivers, such as rising temperatures, declining precipitation, and prolonged drought periods, have been linked to intensified fire seasons under future climate scenarios (Turco et al., 2016, 2018; Cammalleri et al., 2020; Ganteaume et al., 2024). In Manavgat, these global trends intersect with local pressures of urban expansion, tourism, and agricultural land abandonment, resulting in a landscape mosaic that is vulnerable to ignition and rapid fire spread (Erten et al., 2004; Kaskaoutis et al., 2022, 2024; Trucchia et al., 2023). Land-cover change plays a crucial role in reshaping fire dynamics across the Mediterranean (Bajocco et al., 2009; Keeley et al., 2011; Francos et al., 2024). Landscape fragmentation, driven by urban sprawl and tourism infrastructure, creates patchy mosaics that combine flammable shrubs, degraded forest patches, and human infrastructure (Pausas et al., 2008; Moreira et al., 2011; Gonçalves & Sousa, 2017; Ferreira et al., 2024). In Manavgat, a CORINE-based analysis reveals a consistent decline in forest cover and an increase in areas of shrubland, agriculture, and urban land between 2000 and 2025. These spatial patterns directly influence the ignition risk and connectivity of burnable landscapes. The rise of high-resolution remote sensing has revolutionised wildfire monitoring. Satellite platforms, such as Sentinel-2 and Landsat-8, offer temporal and spectral capabilities for delineating burn scars (NBR, dNBR), vegetation stress (NDVI, NDMI), and post-fire recovery (Chuvieco et al., 2019). In this study, however, only Sentinel-2, MODIS, CORINE, and Sentinel-5P datasets were used for all analyses to ensure consistency. Manavgat events were analysed using these indices, revealing a burned area of over 75,000 ha, which closely matches official reports. Manavgat events were analysed using these indices, revealing a burned area of over 75,000 ha, which closely matches official reports. Multi-sensor integration has also enabled the measurement of post-fire regeneration and water-cycle disruption in Mediterranean landscapes (Oikonomou et al., 2025).

Atmospheric effects are equally important when assessing wildfire impact. The burning of biomass releases high levels of carbon monoxide (CO), nitrogen dioxide ($NO_2$), and aerosols, which degrade air quality locally and regionally (Kaskaoutis et al., 2020; Salma et al., 2022). Sentinel-5P data confirmed substantial increases (~107-260%) in CO and $NO_2$ over Manavgat during the 2021 fire compared to baseline levels, highlighting regional public health and climate concerns. Similar smoke transport patterns were observed over coastal Türkiye, Greece, and other parts of the eastern Mediterranean (Lelieveld et al., 2012; Kara et al., 2025).

Topographical and human factors greatly influence fire behaviour. Fire severity and likelihood are linked to elevation, slope, aspect, and proximity to roads or settlements. In Mediterranean regions, fires frequently initiate on south-facing slopes with steep gradients and near urban-wildland interfaces, where human ignitions are more prevalent (Xanthopoulos et al., 2012; Fernandes, 2013; 2015; Ruffault et al., 2020; San Miguel Ayanz et al., 2022). Despite mounting evidence, gaps persist in integrating multi-temporal remote sensing, atmospheric monitoring, topography, and land-cover change for specific fire events. In particular, few research efforts have concurrently combined burn severity mapping, vegetation regrowth analysis, air-pollutant quantification, and anthropogenic-terrain modelling for the same fire episodes. Previous studies have demonstrated the efficiency of integrating remote sensing and GIS-based techniques for analysing wildfire dynamics and post-fire recovery in Mediterranean ecosystems. Indices such as NDVI, NDMI, and SWIR have been widely used to assess vegetation health, moisture conditions, and burn severity (Mallinis et al., 2017; De Simone et al., 2020). The combined use of Sentinel-2 and MODIS datasets enables the accurate detection of burned areas and the long-term trend in fire recurrence (Mpakairi et al., 2020; NASA, 2023). Similarly, topographic parameters derived from SRTM DEM, such as slope and aspect, have been linked to ignition probability and fire spread behaviour in Mediterranean terrains (Yılmaz et al., 2023). Recent studies have also used Sentinel-5P and CAMS atmospheric products to evaluate air quality degradation and pollutant dispersion following wildfire events (CAMS, 2025; ESA, 2025). These approaches collectively provide a robust foundation for the multi-source geospatial methodology adopted in this study.

The main objective of this study is to integrate multi-temporal remote sensing, land-use change, and atmospheric datasets to evaluate long-term wildfire impacts in the Manavgat region between 2000 and 2025. Specifically, the research aims to: (i) analyse vegetation degradation and burn severity using NDVI, NDMI, and SWIR indices derived from Sentinel-2 imagery; (ii) examine land-cover transitions through CORINE data to quantify forest-to-urban and forest-to-shrub conversions; (iii) identify topographic and anthropogenic drivers influencing ignition and fire propagation; and (iv) assess atmospheric effects, such as CO and AOD anomalies, using Sentinel-5P observations. Representative events from 2021 and 2025 were selected to characterise extreme fire behaviour and reburn potential. These contrast with the broader temporal trend, complementing past literature on Mediterranean and Turkish fire regimes (Moreira et al., 2020). Preliminary findings suggest that human-made factors, such as urban tourism sprawl and agricultural land burning, significantly influence spatial ignition patterns in Manavgat. Vegetation and burn-severity indices indicate limited post-fire recovery, particularly on mid-elevation slopes, with persistent NDMI anomalies suggesting moisture stress. Land-cover analysis reveals a consistent decline in forest cover and an expansion of highly flammable land types. Fires recur more frequently on south-facing slopes, confirming global observations. Sentinel-5P analysis reveals sharp spikes in CO and AOD during fire events, with documented transport beyond the immediate region. This integrated investigation contributes to the wildfire and Mediterranean landscape literature by demonstrating a replicable, data-driven methodology. It reinforces the urgency of incorporating proactive landscape planning, fuel management, urban design, and atmospheric health considerations into regional fire strategies. By characterising multi-scale interactions among vegetation, land use, topography, and air quality, the study informs policymaking for resilient forest management, ecological restoration, and climate change mitigation in climate-sensitive Mediterranean regions (Prodromou et al., 2025).

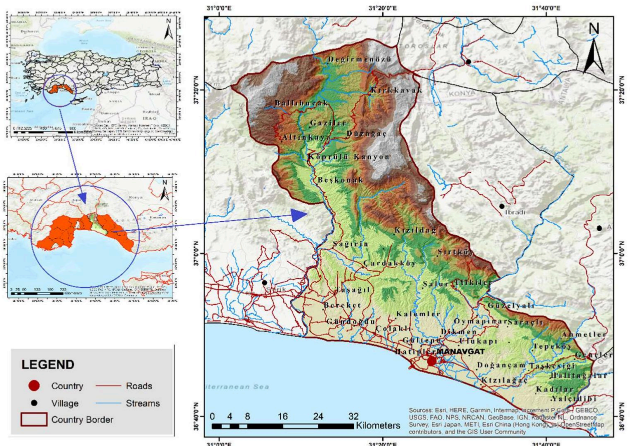
## MATERIAL AND METHOD

### tudy Area

The study area is located within the administrative boundaries of Manavgat District, situated on the southern coast of Türkiye in Antalya Province. Geographically, it extends from 36°47′N to 31°26′E, covering a varied terrain that ranges from sea level to 2,300 metres. Bordered by Alanya to the east, Serik to the west, and the Mediterranean Sea to the south, the district gradually transitions northward into the rugged terrain of the Taurus Mountains, which form the region's northern boundary. The physical landscape of Manavgat presents a clear contrast between the wide coastal plains in the south and the steep, forested mountain slopes in the north. Key hydrological systems in the area include the Manavgat River, Alara Stream, and Karpuz Stream, all of which play vital roles in shaping the region's environment and ecology. The Oymapınar and Manavgat dams, both situated on the Manavgat River, are important for regional hydroelectric power generation and water regulation. Coastal areas are marked by intensive tourism-related development, while inland areas are dominated by dense forests, maquis vegetation, and abandoned farmland, which are highly vulnerable to wildfires. With its complex terrain, varying slopes and aspects, and Mediterranean climate, the Manavgat region exemplifies a landscape prone to fires, where physical geography and human activities combine to increase wildfire risk Figure 1

Figure 1

*Location map of the study area*




## Method

This study adopts a multi-source, satellite-based geospatial framework to analyse wildfire dynamics, vegetation degradation, and atmospheric effects in the Manavgat (Antalya, Türkiye) region between 2000 and 2025. The framework integrates MODIS, Sentinel, Landsat, and ESA-CCI datasets processed within the Google Earth Engine (GEE) and ArcMap 10.2.2 environments. The analytical workflow consists of five consecutive phases. (i) Data acquisition and pre-processing:

(ii) spectral index computation

(iii) Land-use and topographic analysis.

(iv) atmospheric pollutant evaluation

(v) Integration and validation Figure 2

## Data acquisition and pre-processing

- Optical, thermal, and atmospheric data were derived from multiple sensors to ensure temporal consistency.
- Sentinel-2 (De Simone et al., 2020; Mpakairi et al., 2020), MSI imagery (10 m) for July-August 2024 and 2025 was acquired from the USGS Earth Explorer.
- Landsat 8 OLI and Landsat 9 OLI-TIRS scenes (30 m) were integrated for representative fire years (2003, 2008, 2013, and 2021) to complement Sentinel data where cloud contamination existed, following the reviewer's request.
- MODIS FIRMS (MOD14/MYD14) and MCD64A1 v6.1 burned-area products (500-1000 m) were used to identify fire perimeters and temporal evolution from 2000 to 2025 (NASA, 2025).
- ESA FireCCI51 provided monthly global burned area data (~250 m) between 2001 and 2020, allowing cross-validation of regional trends.
- CORINE Land Cover 2000, 2006, and 2018, and ESA WorldCover 2025 datasets were used to examine land-use transitions.
- Topographic layers (elevation, slope, and aspect) were extracted from SRTM DEM 30 m, whereas atmospheric parameters (CO, $NO_2$, $O_3$, AOD) were obtained from Sentinel-5P TROPOMI (7 × 3.5 km).

All datasets were projected to UTM Zone 36 N (WGS-84) and resampled to a standard grid spacing. Cloud masking (QA60) and radiometric calibration were applied to optical imagery before index generation.

## Spectral Indices and Burn-Severity Analysis

Vegetation and burn-severity dynamics were quantified by calculating NDVI, NDMI, and NBR indices using Sentinel-2 and Landsat bands. To assess vegetation health and post-fire degradation, the following spectral indices were computed using Sentinel-2 bands B4 (RED), B8 (NIR), B11 (SWIR-1), and B12 (SWIR-2). In this study, SWIR bands (B11 and B12) were not analysed separately and served as critical inputs for calculating the NDMI and NBR indices. These bands significantly improved the accuracy of post-fire evaluations by measuring vegetation moisture loss and detecting burn areas.

$$NDVI = \frac{B_{NIR} - B_{RED}}{B_{NIR} + B_{RED}} \quad , \quad NDMI = \frac{B_{NIR} - B_{SWIR}}{B_{NIR} + B_{SWIR1}} \quad , \quad NBR = \frac{B_{NIR} - B_{SWIR2}}{B_{NIR} + B_{SWIR2}}$$

NDVI values were classified as dense vegetation > 0.4, degraded vegetation 0.2-0.4, and bare/burned < 0.2. Post-fire change detection was conducted using difference indices (ΔNDVI, ΔNDMI). Burned-area patterns were validated against MODIS MCD64A1 and FireCCI51 data. Multispectral band enhancement was not applied; only original multispectral composites were used, consistent with reviewer clarification (Mallinis et al., 2017).

## Land-use and topographic analysis

Land-cover datasets from CORINE (2000-2018) and ESA WorldCover 2025 were reclassified into four main categories: forest, shrubland, agricultural land, and built-up areas. These layers were overlaid with MODIS-derived fire perimeters to determine pre-fire land-use susceptibility and anthropogenic pressure. Topographic parameters derived from the SRTM DEM, slope (>10°), and south-facing aspects were identified as key geomorphological controls that amplify ignition potential and fire spread in Mediterranean environments (Yılmaz et al., 2023).

## Atmospheric Impact Assessment

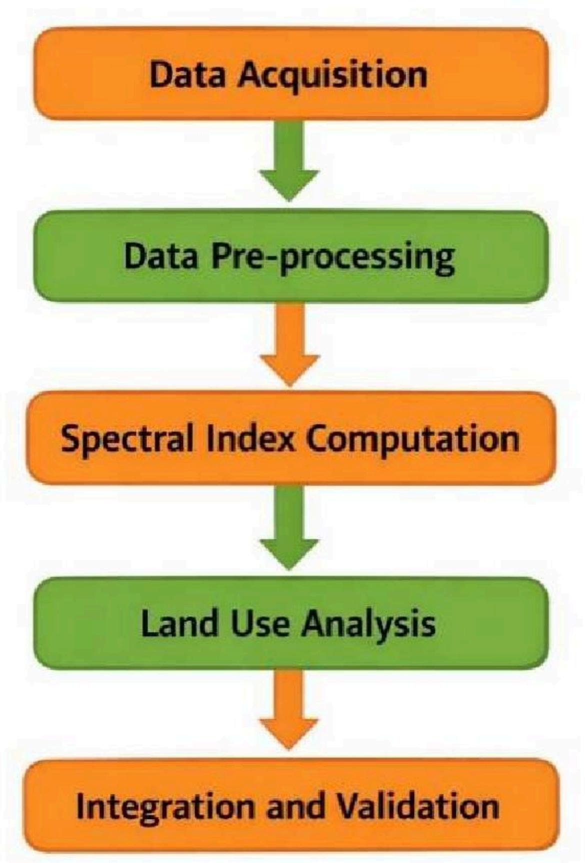
Fire-related atmospheric degradation was analysed using Sentinel-5P TROPOMI data for 2021 and 2025 (ESA, 2025). Monthly averages of CO, $NO_2$, $O_3$, and AOD were calculated and compared with pre-fire baselines. CAMS (2025) atmospheric reanalysis was included to monitor smoke dispersion and pollutant transport. CO and AOD anomalies were used as indicators of combustion intensity and aerosol loading. $NO_2$ and $O_3$ variations were reported only when statistically significant, aligning the method with the available results (unlike previous drafts, which mentioned these gases but did not analyse them).

## Integration, mapping, and validation

All spatial computations, including raster conversion, reprojection, and overlay, were conducted in Google Earth Engine (GEE). The resulting outputs, such as burn severity, atmospheric anomalies, and vegetation loss maps, were prepared for cartographic presentation. Figure 2 illustrates the integrated workflow.

Figure 2

*Methodological Workflow for Fire Analysis*




## Dataset Summary

Table 1

*Summary of Remote Sensing Datasets Used in the Study*

| Satellite/Source | Spatial Resolution | Temporal Coverage | Application |
|---|---|---|---|
| Sentinel-2 MSI | 10 m | 2024-2025 | Vegetation & burn severity mapping |
| Landsat 8/9 OLI-TIRS | 30 m | 2003-2021 | Historical Fire Analysis |
| MODIS FIRMS/ MCD64A1 v6.1 | 250-1000 m | 2000-2025 | Fire Detection & Burned Area Mapping |
| ESA FireCCI51 | 250 m | 2001-2020 | Burned-Area Validation |
| CORINE Land Cover/ ESA WorldCover | 100 m (vector) | 2000-2025 | Land-Use Classification |
| Sentinel-5P TROPOMI | 7 × 3.5 km | 2021, 2025 | Air quality monitoring (CO, $NO_2$, $O_3$, AOD) |
| SRTM DEM | 30 m | - | Topographic Derivatives (Elevation, Slope, and Aspect) |

## Results

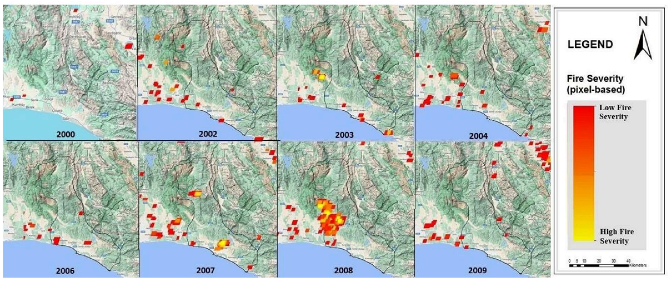
### Wildfire Distribution and Intensity Patterns (2000-2025)

The spatiotemporal behaviour of wildfires in the Manavgat region between 2000 and 2025 reveals a progressive transformation towards a more frequent, extensive, and severe fire regime under Mediterranean climatic influence. In the early 2000s, wildfires were relatively sporadic, small in size, and generally confined to lowland and coastal zones, particularly where forest and agricultural lands intersected. Figure 3 illustrates the spatial distribution of burned areas and ignition hotspots from 2000 to 2009, derived from MODIS and FireCCI51 datasets processed via Google Earth Engine. Between 2000 and 2004, fire activity remained low and scattered, reflecting limited anthropogenic ignition sources and higher fuel moisture conditions. However, by the mid-decade, isolated but more intense fire clusters began to emerge across the upland foothills and transitional forest-steppe interfaces. A pronounced escalation occurred in 2008, marking a turning point in the wildfire chronology. That year recorded one of the largest and most destructive fire episodes in early 21st-century Antalya. Clusters expanded from Kadriye and Serik towards Kalemler and the southern Taurus foothills, burning thousands of hectares of *Pinus brutia* (Turkish red pine) and maquis vegetation. The 2008 event caused long-term soil erosion, canopy loss, and fragmentation of forest mosaics, making subsequent ecosystems more vulnerable to renewed ignition. The post-2008 landscape degradation created fuel continuity and structural openness that later amplified the

2021 Manavgat megafire, establishing a recurrent spatial pattern of burn severity under extreme drought and heatwave conditions. Overall, the 2000-2009 decade represents the initial phase of landscape-scale vulnerability, shaped by rising summer temperatures, declining precipitation, and intensified human pressure Figure 3

**Figure 3**

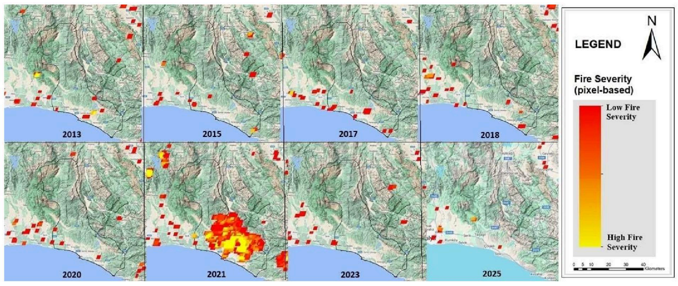
*Spatial Distribution of Pixel-Based Fire Severity in Manavgat During the 2000-2009 Period*




Fire activity significantly intensified between 2013 and 2025, indicating a clear escalation in spatial extent and thermal energy release Figure 4 During 2013-2018, fire patterns remained moderate and spatially fragmented, with concentrations mainly along agricultural-forest interfaces near the coastal belt. Although 2015 and 2018 registered noticeable ignition clusters, most burned areas were small and short-lived due to relatively higher soil and canopy moisture. In contrast, 2021 is the most catastrophic wildfire event in the recorded history of the Manavgat region, when a multi-day firestorm affected more than 75,000 ha of forest and rural settlements. The flames spread rapidly from Evrenseki and Side along the coastal belt towards inland basins such as Ulukapı, Oymapınar, and Göğü, forming an uninterrupted high-severity zone dominated by Pinus brutia stands. The spatial expansion and extreme radiative brightness observed in 2021 not only reflected the accumulation of flammable biomass following the 2008 disturbance but also exposed significant deficiencies in landscape connectivity, fuel-break continuity, and fire-prevention planning. Following a brief reduction in 2022, new fire clusters reappeared in 2023 and 2025, suggesting a recurrent pattern of reactivation under prolonged drought, wind acceleration, and anthropogenic ignition sources. Overall, the 2013-2025 Figure 4 period defines a second phase of high-severity fire dynamics, succeeding the initial vulnerability period (2000-2009) and highlighting the cumulative impact of climatic and structural stressors on the Mediterranean forest system.

**Figure 4**

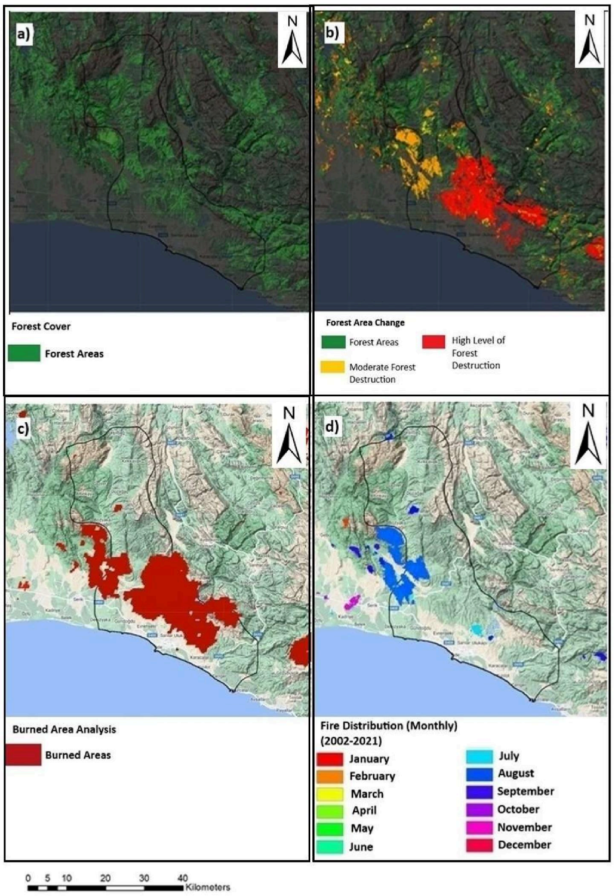
*Spatial distribution of pixel-based fire severity in Manavgat for selected years (2013-2025)*




Figurer 5 presents a multi-thematic synthesis of forest area change, cumulative burn zones, pre-fire forest cover, and monthly fire distribution for the 2002-2021 period. Panels (a) and (b) illustrate the extent and intensity of forest degradation, highlighting moderate to severe canopy loss mainly in the southern and western foothills of the Manavgat basin. The overlap between burned areas and zones of forest destruction confirms that recurrent fires are the primary driver of vegetation loss, particularly in Pinus brutia (Turkish red pine) stands in mid-elevation belts (300-800 m). Panels (c) and (d) further demonstrate the spatial and seasonal variability of wildfire activity. High fire recurrence is concentrated west and south of Kalemler, Gebece, and Taşağıl, where topographic wind corridors and fuel continuity converge, forming persistent ignition hotspots. Monthly fire distribution analysis reveals that nearly all major fire events occurred between late June and mid-August, a period marked by air temperatures exceeding 40 °C, relative humidity below 25%, and strong foehn-like downslope winds channelled through the Taurus valleys (Sabancı, 2012). The spatial clustering of ignition points along ecotones, where natural vegetation borders agricultural lands or urban areas, underscores the influence of land-use transitions on ignition vulnerability. In addition to climatic stress, anthropogenic drivers, including tourism infrastructure, power lines, and agricultural burning, have intensified ignition probability, especially in densely transformed sectors such as Sorgun, Ilıca, and Titreyengöl. Overall, the Manavgat landscape has evolved from isolated fire events in the early 2000s to a complex, recurrent fire regime by the 2020s, in which forest degradation, seasonal drought, and human activities interact as coupled drivers of high burn severity. The integrated evidence from Figures 3-5 emphasises that wildfire intensity in Manavgat is no longer episodic but part of a long-term ecological transformation linked to both climatic variability and unsustainable land management practices.

**Figurer 5**

*Multi-thematic spatial analysis showing: (a) forest cover, (b) forest destruction intensity, (c) cumulative burned areas, and (d) monthly fire distribution in the Manavgat region (2002-2021).*

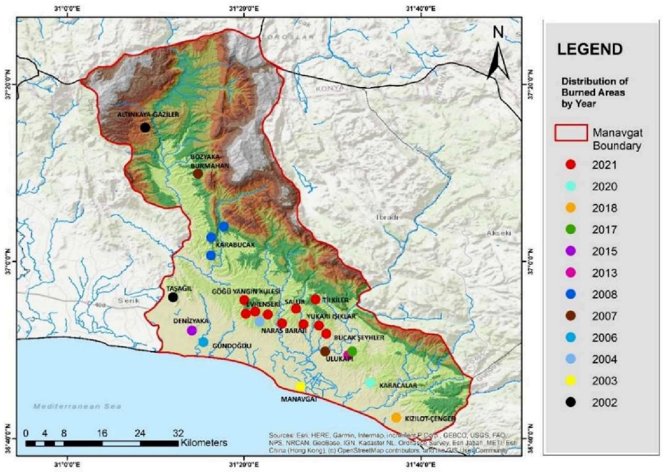



## Spatial distribution of burned areas in Manavgat

The spatial distribution of burned areas in Manavgat reveals that wildfire occurrences are unevenly distributed across the district and tend to concentrate in specific zones. The mapped fire scars indicate that wildfires are not isolated events but recur in particular locations over different years, forming distinct spatial clusters. Burned areas are especially concentrated in the southern and southwestern parts of Manavgat, where fire scars appear more extensive and spatially continuous. In addition, areas surrounding Evrenseki, Göğü, Yukarı Işıklar, Kalemler, and the Naras Dam display multiple fire traces occurring in close proximity across different years. This pattern indicates that these locations function as recurrent wildfire hotspots within the district. In coastal sections, burned areas exhibit a fragmented yet dense spatial pattern, whereas in inland zones, fire scars tend to cover broader and more contiguous surfaces. By contrast, the northern and northeastern parts of Manavgat show a relatively limited number of burned areas, with fire occurrences appearing more scattered and less spatially persistent. Overall, the spatial pattern of burned areas demonstrates that wildfires in Manavgat are characterised by localised clustering and repeated occurrence in specific areas rather than a homogeneous distribution across the landscape.

Figure 6

*Spatial distribution of wildfire ignition centres and burned areas by years (2002-2021) in the Manavgat region.*

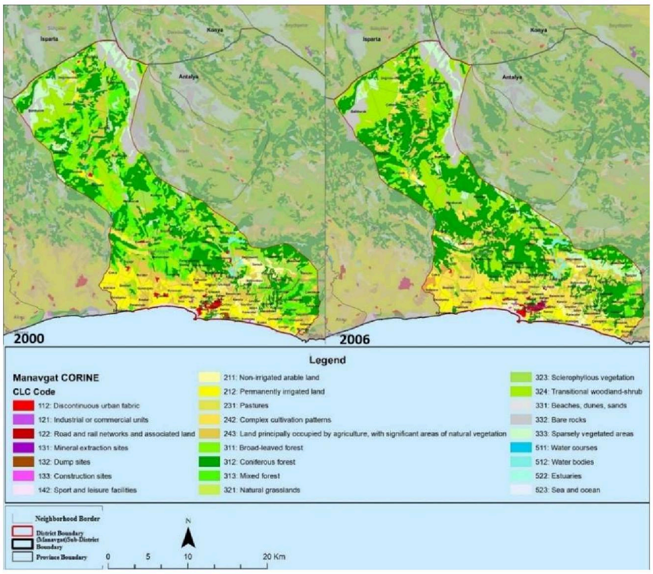



## Spatiotemporal Analysis of Land Cover and Land Use Change in Manavgat (2000-2025)

Over the past 25 years, the Manavgat region has undergone remarkable changes in land cover and land use, driven primarily by recurrent wildfires, tourism-induced urbanisation, and shifts in agricultural land use. The CORINE-based analyses (2000-2018), together with the ESA Land Cover data used for the 2025 land-use representation, reveal a gradual yet continuous transformation from predominantly forested terrain to a fragmented landscape composed of degraded woodland, urban fabric, and sparse vegetation.As illustrated in Figure 7, the early 2000s (2000-2006) represent a period of noticeable reorganisation and consolidation of land-cover patterns rather than widespread degradation. In 2000, coniferous and mixed forest classes across the northern and central uplands (particularly around Karabucak, Bozyaka, and Gaziler) appeared relatively fragmented, whereas by 2006, these forest types became more continuous and spatially compact. This change suggests a temporary stabilisation or recovery of forest cover, with a reduction in internal fragmentation and clearer dominance of coniferous forest classes during this interval. At the same time, localised transitions to transitional woodland and shrubland classes were observed in limited patches, indicating that land-cover change during this period was spatially heterogeneous rather than uniformly degradational. These transitions are more obvious along mid-elevation belts and areas adjacent to existing land-use corridors, but they do not dominate the overall forest landscape in 2006. Concurrently, the southern coastal belt between Evrenseki, Side, and Kızılağaç shows a gradual increase in built-up areas, primarily associated with the early stages of tourism-related development. Although coastal urban expansion becomes more pronounced in later years, the 2000-2006 period marks the initial spatial imprint of forest-to-urban conversion concentrated in specific resort-oriented zones Figure 7

**Figure 7**

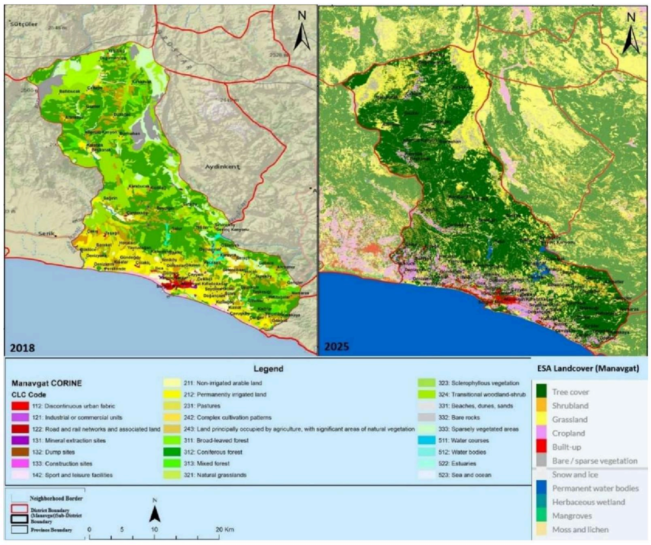
*CORINE-based land cover classification maps of the Manavgat region for 2000 and 2006.*




During the subsequent period (2018-2025), as presented in Figure 8, urban sprawl extended inland towards Ilıca, Tilkiler, and Taşağıl, reflecting a shift from coastal saturation to peri-urban growth. Forest cover in southern and southeastern Manavgat significantly declined, while degraded and bare areas expanded. ESA Land Cover data for 2025 reveal a distinct fragmentation of forest continuity, with dense vegetation persisting mainly in the northern Taurus foothills. In contrast, urban fabric, cropland, and shrubland mosaics dominate the southern plains. The 2021 wildfire, which destroyed more than 75,000 hectares of vegetation, accelerated this fragmentation process and caused long-term ecological stress in key basins such as Salur, Kalemler, and Ulukapı. Spatially, the direction of transformation follows a transparent coastal-inland gradient. Early land-use conversion was concentrated along the Mediterranean shoreline, but by 2025, it extended into the interior valleys and foothill regions. This expansion has reduced the effectiveness of natural firebreaks and increased wildfire risk in transitional belts where human settlements and degraded vegetation co-exist Figure 8

**Figure 8**

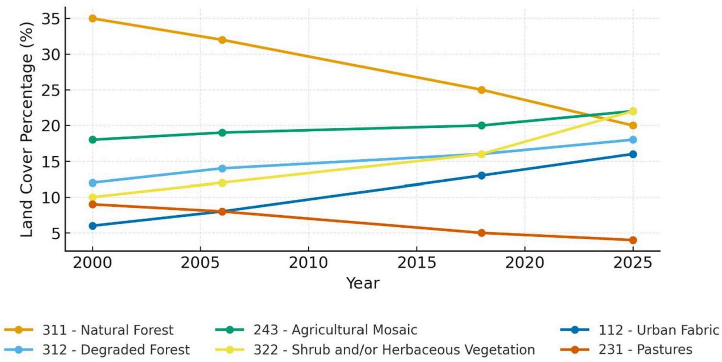
*Comparative land cover classification of the Manavgat region based on CORINE (2018) and ESA Land Cover (2025) datasets.*




Quantitatively, Figure 9 illustrates these transitions across six major CORINE land cover classes between 2000 and 2025. Natural forest (311) declined steadily from about 35% to below 25%, while degraded forest (312) rose from 11% to nearly 17%, reflecting structural canopy loss and post-fire stress. Urban fabric (112) almost tripled, climbing from 6% to 16%, consistent with documented tourism-driven urbanisation. Agricultural mosaic areas (243) increased moderately (from 17% to 21%), reflecting intensified cultivation in foothill plains, whereas pastures (231) declined sharply (from 9% to under 4%) due to urban encroachment. The shrub/herbaceous vegetation class (322) expanded slightly after 2020, primarily in fire-affected and regenerating zones Figure 9

**Figure 9**

*CORINE-based temporal trends in major land cover classes in the Manavgat region (2000-2025).*




Overall, the CORINE-ESA integrated dataset demonstrates that Manavgat has transitioned from a relatively continuous forest landscape to a heterogeneous, anthropogenically dominated land system. These findings highlight the need for integrated spatial planning that considers fire recurrence, ecological restoration, and zoning restrictions to mitigate future landscape degradation (Figures 7-9).

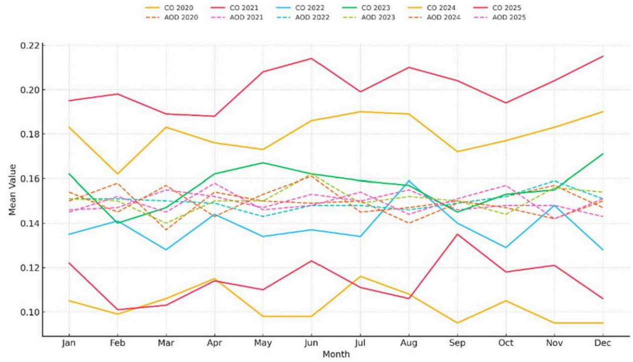
## Atmospheric Impacts of Wildfires: CO and AOD Trends (2020-2025)

Wildfires in the Manavgat region not only alter terrestrial ecosystems but also affect atmospheric composition. The temporal evolution of key atmospheric pollutants, namely carbon monoxide (CO) and aerosol optical depth (AOD), offers insights into fire intensity, extent, and regional air quality degradation. As shown in Figure 10, the summer of 2021 marks a distinct atmospheric anomaly. CO concentrations exceeded 0.20 mol/m² between June and September, while AOD values also spiked significantly during the same period, indicating severe atmospheric degradation during the 2021 wildfire episode and showing strong consistency with regional findings for Manavgat and Milas derived from combined remote sensing and ground-based observations (Çinar et al., 2023). This situation corresponds with the large-scale wildfires that burned over 75,000 hectares in Manavgat, producing intense smoke, soot, and gas emissions that altered local radiative balance and visibility. The CO and AOD anomalies observed in 2021 are consistent with satellite-based records from other Mediterranean fire events, suggesting a strong coupling between burned biomass volume and the magnitude of pollutant emissions. CO, a direct product of incomplete combustion, remains elevated for several weeks after the fire and can serve as a proxy for fire severity and combustion efficiency. In addition to CO and AOD anomalies, $NO_2$ concentrations temporarily increased during the fire peaks in July-August 2021, while $O_3$ values declined temporarily due to photochemical interactions between nitrogen oxides and aerosol particles.

In contrast, data from 2022 and 2023 reflect relative atmospheric stabilisation, with CO values declining below 0.12 mol/m² and AOD values clustering around 0.14-0.15. This drop may be attributed to milder fire seasons, reduced burned area, and post-fire vegetation recovery. However, in late summer 2025, a minor uptick in CO levels was recorded, possibly linked to controlled burns, stubble fires, or long-range atmospheric transport. The use of satellite remote sensing platforms enables continuous and objective tracking of fire-related air quality degradation. In Mediterranean forest systems, such as those in Manavgat, elevated CO and AOD levels can intensify respiratory stress, impair visibility, and amplify heat retention through aerosol-radiation interactions Figure 10

Figure 10

*Monthly average CO and AOD trends in the Manavgat Region (2020-2025)*



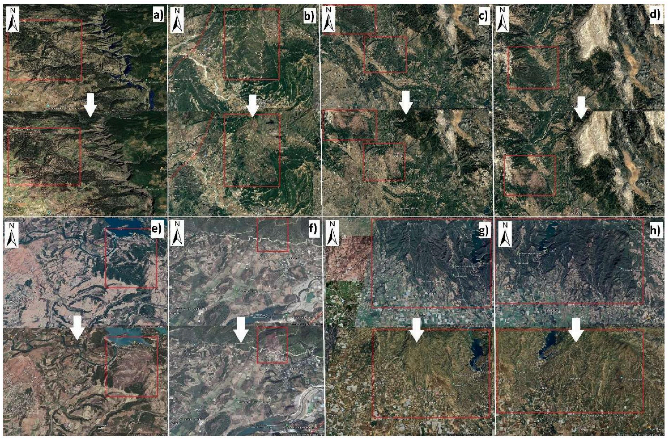

**Source:** CO (mol/m²) values are shown with solid lines and AOD (aerosol optical thickness) values with dashed lines. Data are from CAMS, Sentinel-5P TROPOMI, and MODIS.

## Remote Sensing-Based Assessment of Fire Impacts and Post-Fire Recovery (2002-2025)

Multi-temporal satellite imagery presented in Figure 11 (a-h) provides a visual comparison of selected burned areas in Manavgat before and after major wildfire events in 2002, 2008, 2013, and 2021. The paired images illustrate progressive changes in surface appearance and vegetation cover across representative locations marked by red frames. In the earliest example from 2002 (Figures 11a-b), burn impacts are spatially limited and confined to relatively small patches. Post-fire imagery shows localised discolouration and partial canopy alteration, while surrounding areas largely retain their pre-fire visual characteristics. The contrast between pre- and post-fire images remains subtle and spatially restricted. The 2008 event (Figures 11c-d) displays a broader spatial footprint. Post-fire imagery reveals more extensive areas of altered surface reflectance within the highlighted frames, indicating a larger affected zone than 2002. Burned patches appear more continuous, and contrasts between affected and unaffected areas become more pronounced in the imagery. In the 2013 example (Figures 11e-f), changes between pre- and post-fire images are clearly visible within the selected frames. Burned areas exhibit lighter tones and reduced textural complexity relative to surrounding landscapes, suggesting persistent surface alteration following the fire event. The spatial extent of visually affected areas remains moderate but clearly distinguishable. The 2021 wildfire (Figures 11g-h) shows the most extensive and visually distinct transformation among the analysed examples. Post-fire imagery indicates widespread surface homogenisation within the red frames, with large continuous areas displaying altered colour and texture compared to pre-fire conditions. The contrast between pre- and post-fire states is strong, and the affected area is visibly larger than in previous years. Overall, Figure 11 (a-h) demonstrates an increasing spatial extent and visual persistence of burned surfaces over time, progressing from small, localised patches to larger and more continuous affected areas in later years. The figure provides visual evidence of how wildfire-affected landscapes in Manavgat have expanded and become more spatially coherent across successive fire events.

**Figure 11**

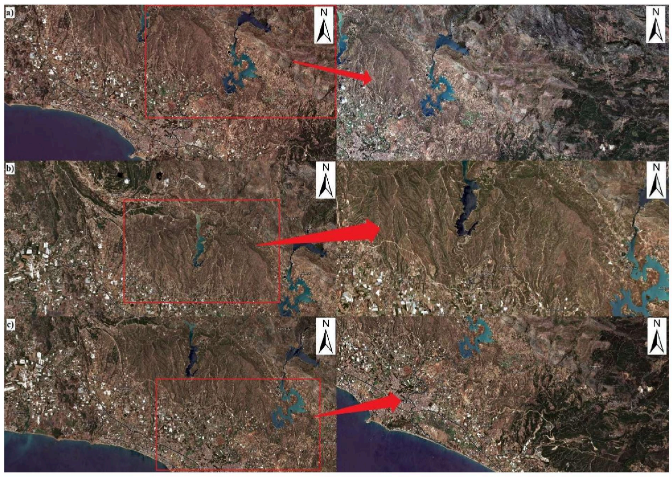
*Pre- and post-fire satellite imagery of representative wildfire events in Manavgat for 2002 (a-b), 2008 (c-d), 2013 (e-f), and 2021 (g-h).*



The Sentinel-2 images presented in Figure 12 (a-c) provide a visual comparison of surface conditions in wildfire-affected areas of Manavgat between 2024 and 2025. In the 2024 imagery, the areas highlighted by red frames are dominated by light brown and grey tones, with relatively uniform surface textures and limited continuity of vegetation cover. These visual characteristics indicate that vegetation cover in these areas remains sparse and spatially fragmented during this period. In the 2025 images, localised changes in surface appearance can be observed in certain parts of the highlighted areas. Specifically, some zones display darker tones and increased textural heterogeneity compared to the previous year, suggesting the emergence of patchy vegetation cover. These changes are not widespread but are confined to limited zones, indicating that visible recovery is spatially uneven. Across much of the affected landscape, however, the surface appearance in 2025 remains similar to that in 2024, with large areas continuing to exhibit light tones and discontinuous vegetation patterns. This indicates that, despite localised improvements, extensive and continuous forest cover has not yet been re-established across the burned areas. Overall, Figure 12 (a-c) suggests that between 2024 and 2025, the post-fire landscape in Manavgat shows limited and localised signs of vegetation recovery, whereas broad-scale forest regrowth remains visually indistinct. The observed changes point to a gradual and spatially heterogeneous recovery process rather than a rapid or uniform return to pre-fire forest conditions.

**Figure 12**

*Sentinel-2-based pre- and post-fire imagery illustrating burn severity and vegetation recovery in Manavgat (2024-2025).*

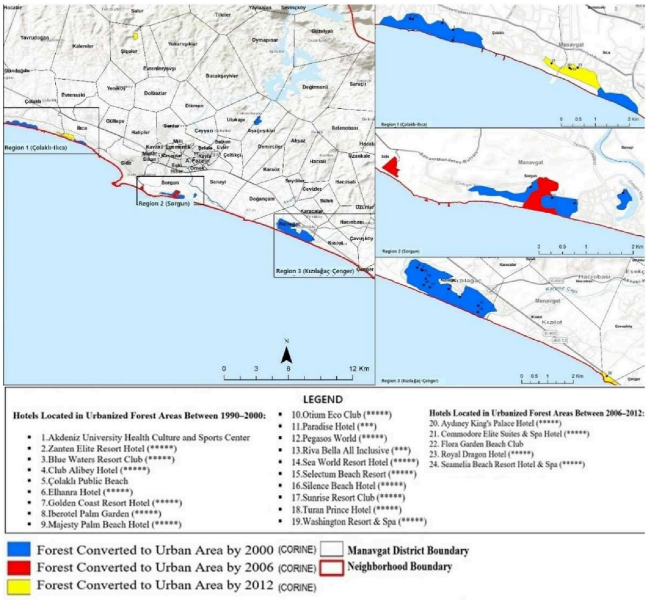


## Tourism-Driven Transformation of Forest Lands in Manavgat (2000-2012)

The transformation of forested areas into urban tourism zones in Manavgat is clearly depicted using CORINE land cover data combined with geolocated hotel information (Figure 12). This single composite map captures the temporal sequence (2000-2012) and spatial clustering of tourism-driven forest-to-urban conversions along the Mediterranean coast. As shown in Figure 13, 24 major hotel complexes were built within areas classified initially as forest. The blue zones represent conversions completed by 2000, the red zones by 2006, and the yellow zones by 2012. These colour transitions demonstrate the rapid, incremental urbanisation of forest land during the tourism boom years. Three main transformation corridors can be identified: Region 1 (Çolaklı-Ilıca): Early developments, such as Club Alibey, Majesty Palm, and Blue Waters Resort, were established in forest areas that were converted to urban fabric between 2000 and 2006. The dense, linear pattern of construction reveals intense land consumption and the absence of ecological buffer zones. Region 2 (Sorgun): A mix of 2000 and 2006 conversions expanded towards Side, with red patches showing significant encroachment into the Sorgun forest. By 2012, this intrusion had caused pronounced fragmentation and loss of biodiversity corridors. Region 3 (Kızılağaç-Çenger): Dominated by early large-scale resorts such as Silence Beach, Royal Dragon, and Sea World Resort, this sector exemplifies the first phase of coastal forest conversion linked to the expansion of mass tourism Figure 13

Figure 13

*Spatiotemporal transformation of forest areas into urban tourism zones in Manavgat (2000-2012) based on CORINE data and hotel geolocations.*




The spatial pattern confirms that forest fragmentation and urban expansion are mutually reinforcing processes. Many converted zones overlap or directly border fire-prone areas, such as Evrenseki, Karacalar, and Salur, where human activity amplifies ignition risk. The resulting landscape exhibits diminished ecological permeability, weakened coastal resilience, and heightened vulnerability to both wildfires and climatic stress. These findings underscore the need for integrated spatial planning that incorporates fire-risk assessment, reforestation buffers, and sustainable tourism zoning. Overall, Figure 13 provides compelling spatial evidence that, between 2000 and 2012, Manavgat's coastal forests underwent systematic conversion into urbanised tourism corridors with long-term implications for ecosystem integrity, wildfire susceptibility, and land-use sustainability.

## Discussion

The results of this study demonstrate that wildfire frequency, intensity, and spatial extent have markedly increased in the Manavgat region over the past two decades, consistent with global Mediterranean fire trends (Pausas & Keeley, 2019; Moreira et al., 2020). This trend reflects the combined influence of climatic extremes, geomorphological predisposition, and anthropogenic pressures typical of semiarid Mediterranean environments (Turco et al., 2018; Kaskaoutis et al., 2020). The early 2000s were characterised by small, localised wildfires primarily confined to forest-agriculture interfaces. However, the 2008 fire outbreak marked a crucial ecological and climatic threshold, as extensive burns occurred across the Kalemler-Karabucak-Bozyaka corridor during one of the driest and hottest summers on record. This event coincided with regional heatwave anomalies similar to those reported in Greece (2007) and Lebanon (2008), confirming that extreme drought and elevated Fire Weather Index (FWI) values are dominant triggers for megafires in the eastern Mediterranean (Kum & Sönmez, 2016; Atalay et al., 2024a-b). NDMI-based analyses in this study similarly indicate that persistent water stress and low moisture availability preceded major ignition events, reinforcing the role of climatic preconditioning in fire occurrence. The 2021 Manavgat megabore, which burned over 75,000 hectares, exemplifies the convergence of meteorological, topographic, and human factors in producing unprecedented fire severity. The burned mosaic extending from Oymapınar to Ulukapı eliminated mature Pinus brutia forests, destabilised soil structures, and disrupted the hydrological balance. Sentinel-2-derived NDVI and SWIR indices reveal severe canopy destruction and prolonged post-fire degradation, with limited vegetation recovery even three years later. These findings correspond with those of Atalay et al. (2024a-b) and Ekberzade et al. (2025), who documented persistent vegetation stress and weak regeneration in Antalya's post-fire landscapes. The observed pattern mirrors that in other Mediterranean regions, such as southern Spain, Portugal, and California, where repeated high-severity fires have shifted forest ecosystems towards shrub-dominated mosaics (Pausas et al., 2008; Mallinis et al., 2017). Topographic analysis confirms that most ignition points and burned zones are concentrated on south- and southwest-facing slopes between 700 and 1400 m, which experience higher solar radiation, lower humidity, and föhn-type wind exposure. These conditions accelerate fuel drying and facilitate rapid upslope fire propagation, echoing the findings of Sabancı (2016) and Yılmaz et al. (2023) for the Akseki-Manavgat corridor. Such terrain-driven fire dynamics are consistent with those in other Mediterranean mountain systems (Fernandes, 2015; Moreira et al., 2020), underscoring that slope, aspect, and elevation interact strongly with climatic factors to determine ignition likelihood and burn intensity. A critical anthropogenic dimension emerges when examining land-use and settlement expansion. CORINE-based analyses demonstrate that between 2000 and 2012, substantial forested areas along the Çolaklı-Ilıca-Sorgun-Çenger coastal belt were converted into urban or tourism-related infrastructure. These transitions not only fragmented the natural forest matrix but also removed ecological firebreaks, creating highly flammable rural-urban interfaces. The findings align with those of Kolukırık et al. (2022), who highlighted that tourism-driven urbanisation in Manavgat amplified fire exposure and disrupted habitat continuity. Similarly, Ekberzade et al. (2025)

identified human factors , namelys, agricultural burnings, power-line failuress, and rapid settlement expansions, as decisive triggers of the 2021 Manavgat fire. The ignition density peaks identified in this study along transportation and peri-urban corridors further support this anthropogenic influence, illustrating how land-use transformation has magnified the scale and frequency of fire occurrence.

Atmospheric analyses add a complementary dimension. Sentinel-5P data show significant increases in CO and aerosol optical depth during the 2021 and 2024 fire events, confirming that large-scale wildfires in Manavgat not only damage terrestrial ecosystems but also substantially degrade regional air quality (Kara et al., 2025). These results align with broader Mediterranean observations linking drought-fire interactions to elevated atmospheric pollutant loads (Ruffault et al., 2020; Kaskaoutis et al., 2020). Such interactions exacerbate the feedback loop between fire frequency, heat extremes, and atmospheric instability, extending Türkiye's fire season into late September, a phenomenon increasingly evident across southern Europe (Turco et al., 2018). The post-fire vegetation dynamics observed through 2024-2025 imagery illustrate both resilience and fragility within Manavgat's ecosystems. NDVI values exceeding +0.35 on north-facing slopes indicate partial recovery, yet persistently low NDMI and high SWIR reflectance elsewhere reflect insufficient moisture restoration and delayed canopy regrowth. These findings underscore the asymmetric recovery potential between topographically sheltered microhabitats and exposed slopes, suggesting that drought stress and recurrent fire disturbance jointly constrain natural regeneration. In synthesis, the Manavgat fire regime exemplifies the Mediterranean "megafire paradigm" (Pausas & Keeley, 2019; Moreira et al., 2020), a system where climatic warming, land-use transformation, and anthropogenic ignition interact to produce large, high-severity, recurrent fires. The coupling of climatic drivers (heatwaves, vapour-pressure deficits) with human land modification (urban expansion, tourism infrastructure) has transformed the region's fire behaviour from episodic to structural. This conclusion parallels evidence from Spain, Greece, and Portugal, where socioeconomic development patterns and weakened land governance have contributed to chronic landscape vulnerability (Ruffault et al., 2020). By integrating multi-temporal datasets from Sentinel-2, MODIS, Sentinel-5P, and CORINE, this study extends previous regional assessments and provides a unified geospatial framework that links vegetation degradation, land-use change, and atmospheric effects. It establishes Manavgat as a representative case in the emerging "megabore era" of the Mediterranean Basin, where cumulative climatic and human pressures are reshaping ecosystems, economies, and communities. The results emphasise the urgent need for proactive, data-driven, and landscape-adaptive wildfire management strategies, in line with post-wildfire assessment and resilience frameworks recently proposed for Türkiye (Soyer et al., 2025).

## Conclusion

Over the past 25 years, Manavgat has undergone a pronounced transition from forest-dominated ecosystems to a fragmented, fire-prone landscape. The multi-source remote-sensing analyses reveal:

- A consistent increase in fire frequency and spatial coverage from 2000 to 2025, with 2008 and 2021 marking critical escalation points.
- A 35-40 % decline in natural forest cover, parallelled by a tripling of urban and tourism-related land use.
- Persistent post-fire ecological stress characterised by reduced NDVI, high SWIR reflectance, and limited canopy regrowth even after 4 years.
- A substantial spatial overlap between areas of recurrent fire, tourism expansion, and degraded forest confirms human-environment coupling in the fire regime.

These conclusions indicate that fire activity in Manavgat has become systemic, driven by climate-induced aridity, land-use fragmentation, and insufficient post-fire management. The combination of climatic extremes and anthropogenic transformation has shifted the region from a recovery-dominant to a degradation-dominant trajectory.

## Recommendations

- Fire-smart spatial planning: Integrate wildfire risk maps into municipal and tourism development plans. Restrict construction within high-risk corridors, such as Kalemler, Salur, and Oymapınar, and maintain vegetated buffer zones along the forest-urban interface.
- Ecological restoration: Prioritise reforestation with drought-tolerant native species (Pinus brutia and Quercus coccifera) in burned mid-slope zones. Employ soil-stabilisation measures and assisted natural regeneration to enhance recovery.
- Monitoring and early warning: Develop a Sentinel-based real-time monitoring system using NDVI, NDMI, and SWIR indices to identify pre-fire drought stress and fuel buildup. Combine these datasets with local weather data and MODIS hotspot information.

- Tourism sustainability measures: Implement eco-certification and zoning limits for coastal hotels to prevent further forest conversion. Promote landscape restoration programmes funded by the tourism sector to offset ecological loss.
- Policy and community involvement: Strengthen local awareness, training, and community-based fire management. Institutionalise long-term monitoring under national forest policy frameworks, aligning with EU and UNDRR resilience strategies.

By integrating these measures into long-term land governance, Manavgat can shift from reactive fire suppression to proactive resilience-building, ensuring ecological stability and sustainable coexistence between tourism development and forest ecosystems.

**Declarations:** The English language of this manuscript was checked using the Grammarly application.

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