



Satellite vs. Ground-Based Estimates of Burned Area in Greece: Validation of MODIS MCD64A1 Data Using Fire Service Reports

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Abstract. Wildfires are among the most impactful natural disasters, severely affecting ecosystems, communities, and economies. Their frequency and intensity are increasing across many world regions due to human activities and climate change. In Greece, an increasing trend in catastrophic wildfires poses a major threat to ecological balance and society making effective prevention paramount. Monitoring and modelling wildfires are crucial steps for being able to predict and prevent their consequences, and therefore data of adequate quality is needed. This study compares burned area estimates derived from NASA's MODIS MCD64A1 global product with the Hellenic Fire Service (HFS) records for 2002–2023. The analysis examines spatial and temporal agreement between these widely used datasets at national and regional scales, and evaluates how discrepancies vary across land cover types. The results of the comparison show strong interannual agreement ($R^2 > 0.87$ in five of seven regions), with agreement further strengthening in recent years, as indicated by a mean absolute deviation of only 5% over 2021–2023. At the national scale, MODIS overestimates burned area by 41% overall, but this difference drops to 12% when only natural land covers are considered, mainly reflecting MODIS detection of cropland burning in Thessaly-Central Greece, and Macedonia-Thrace, which is not included in the HFS data. These seasonal differences are most pronounced during September and October in northern and central Greece, whereas lower MODIS burned area estimates characterize Crete and the Aegean islands. These findings highlight the complementary value of satellite and ground-based fire records for the interpretation and use of MODIS burned area products in Mediterranean fire monitoring.

1 Introduction

Wildfires represent one of the most recurrent and damaging natural hazards in the Mediterranean Basin. Over the past decades, Mediterranean countries have experienced thousands of fire events annually, resulting in significant environmental degradation, economic loss, and human casualties (European Commission, Joint Research Centre, 2020). Fire behaviour is shaped by the interaction of climatic conditions, fuel characteristics, and human presence (Bowman et al., 2009). In Mediterranean ecosystems, most wildfire ignitions originate from human activities (Ganteaume et al., 2013), with fire activity concentrated in a few large summer events (Tedim et al., 2018). Extreme fire seasons are increasingly driven by prolonged drought, elevated temperatures, and extreme weather conditions, which are expected to become more frequent due to climate



change (Ruffault et al., 2018). In the Mediterranean basin, and specifically in Greece, climate change points toward higher fire danger and more severe fire regimes in the coming decades (Rovithakis et al., 2022; Rovithakis et al., 2025). Moreover, evolving land use changes, specifically land abandonment and fragmentation, along with forest management decisions, play a crucial role in determining future wildfire trends (Moreira et al., 2020; Koutsias et al., 2013; Pausas and Fernández-Muñoz, 2012).

Greece is among the Mediterranean countries most affected by wildfires (San-Miguel-Ayanz et al., 2013; Turco et al., 2016). From the early 20th century to 2023, the country experienced numerous intense wildfire years, including the catastrophic events in 2007, 2018 and 2023, when burned areas exceeded up to 120,000ha (San-Miguel-Ayanz et al., 2024). According to WWF, the majority of ignitions in Greece are attributed to human activity- intentional or accidental- accounting for more than 95% of total events. In addition to loss of life and property (Radeloff et al., 2023), fires in Greece contribute to severe soil erosion (Shakesby, 2011), leading to ecosystem degradation and biodiversity loss (Pausas and Ribeiro, 2017), including in protected landscapes (Moreira et al., 2020). By releasing stored carbon and reducing the landscape's capacity for sequestration, vegetation loss exacerbates the positive feedback mechanism driving the fire-climate interaction (Bowman et al., 2009; Pellegrini et al., 2018). Understanding the temporal and spatial dynamics of burned areas is therefore critical for improving national fire prevention and management strategies (Chuvieco et al., 2014).

Reliable and consistent fire datasets are essential for analyzing long-term fire regimes and evaluating the effectiveness of management policies. However, in many Mediterranean countries, including Greece, ground-based fire statistics often suffer from inconsistencies in spatial coverage, varying quality-control procedures, and incomplete historical records (Mouillot and Field, 2005; Hantson et al., 2016). These limitations hinder the analysis of large-scale fire patterns and the development of predictive models. To address this challenge, satellite remote-sensing techniques have become indispensable tools for fire monitoring, offering systematic global coverage and temporal consistency (Chuvieco et al., 2019). Among available datasets, NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) provides the MCD64A1 global burned area product, which underpins several international fire and carbon emission inventories such as GFED (Giglio et al., 2018; Randerson et al., 2012; van der Werf et al., 2017).

The MODIS MCD64A1 product provides monthly global burned area estimates at 500m resolution by detecting changes in surface reflectance and thermal anomalies (Giglio et al., 2018). While extensively applied in fire research, its accuracy is influenced by fire size, vegetation type, and topography (Boschetti et al., 2019; Katagis and Gitas, 2022). Cloud cover, spectral confusion between cropland and burned surfaces, and coarse spatial resolution often lead to underestimation of small fires and overestimation in agricultural landscapes. Beyond the internal limitations of the MCD64A1 dataset, burned area estimation faces substantial uncertainty from two external factors: omission errors, often caused by thick smoke masking active fires, and commission errors, arising from false detections in spectrally heterogeneous tropical environments (Giglio et al., 2018; Boschetti et al., 2019; Chen et al., 2023).

In Mediterranean ecosystems, where fires are typically spatially fragmented (Bastarrika et al., 2011), accurate detection is often hindered by coarse spatial resolution and spectral confusion with croplands, leading to frequent underestimation or



65 overestimation of burned areas (Turco et al., 2019; Katagis and Gitas, 2022). According to Boschetti et al. (2019), a global
Stage 3 validation assessment revealed that the Collection 6 MCD64A1 product exhibits commission and omission error rates
of 40.2% and 72.6%, respectively. Ground-based fire records maintained by national fire services complement satellite
observations by providing detailed information on fire location, cause, and suppression activities, though they often lack spatial
continuity. Comparing satellite-derived and ground-based datasets is therefore essential to assess their complementarity,
70 identify potential biases, and improve burned area estimation.

Numerous recent investigations have assessed the concordance between satellite-derived fire data and ground-based records
across various regional and continental domains (Mangeon et al., 2016; Artés et al., 2019).

This research stands as one of the first to investigate wildfire activity in Greece with this level of extensive spatial and temporal
detail. The analysis covers the period 2002–2023, at monthly resolution that allows for a thorough assessment of temporal
75 dynamics. The study compares NASA’s MODIS MCD64A1 global satellite products and official ground-based data from the
Hellenic Fire Service (HFS) for the period 2002–2023, for Greece, bringing two fundamentally different recording methods
together: remote sensing observations and human-based field reporting. It incorporates analyses by region and land-cover type,
which adds value given to the country’s geographic setting and the distinct characteristics of the Mediterranean climate.
Moreover, we assess the temporal consistency, spatial distribution, and statistical agreement between the two datasets, while
80 also explore how discrepancies vary across land cover types and fire sizes, with particular attention to agricultural areas where
satellite misclassification is common.

2 Data and methods

2.1 Study area

Located at the southern tip of the Balkan Peninsula in Southeast Europe, Greece exhibits significant climatic diversity. This
85 variability is largely attributed to its geographical position, extending from 35°N to 42°N latitude and 19°E to 28°E longitude.
The combination of its Mediterranean setting and complex topography gives rise to numerous distinct microclimates across
the country. The analysis is conducted at the level of the seven Decentralized Administrations of Greece; Peloponnese and
Western Greece and Ionian Islands, Macedonia and Thrace, Thessaly and Central Greece, Attica, Crete, Aegean, Epirus and
Western Macedonia (see Supplement Fig. S1).

90 2.2 Ground-based fire data

The ground-based records are compiled and maintained as open datasets from the Hellenic Fire Service (HFS)
(https://www.fireservice.gr/el_GR/synola-dedomenon, accessed on 10 September 2024). The official website of the HFS has
a wide range of information and services concerning the operation and activities of the Corps. There is also free access to a
summary of the data and activities of the Service. In accordance with Law 4305/2014, the open availability and further use of
95 public sector documents, information and data is redefined. The incident archive contains both urban and forestry incidents in



which the HFS intervenes in Excel format. For the study, we used the forest fire archive for each year, which provides detailed information, such as the incident registration number, service, prefecture, date and time of start and extinguishing, forestry department, municipality, region, address, burnt area by type of vegetation, involved personnel, and number of vehicles. From 2021 to present, each recorded incident also includes X and Y geographic coordinates as a point.

100 2.3 Satellite-based fire data

NASA Moderate Resolution Imaging Spectroradiometer (MODIS) MCD64A1 collection 6 burned area product has been selected which has a spatial resolution of 500m (nominal 500m, actual 463m). The MCD64A1 product combines images from both NASA's Terra and Aqua satellites, along with thermal anomalies, and provides burn and quality information for every individual pixel. The MCD64 burned area algorithm integrates 500m MODIS surface reflectance with 1km MODIS active fire
105 detections. By leveraging a spectral index derived from the 1240 and 2130nm bands and analyzing temporal changes, the system applies dynamic thresholds to Terra and Aqua composite data. The algorithm's ability to adjust to changing conditions is driven by cumulative 1km active fire detections, which guide the selection of training data and the calculation of prior probabilities. Each burned pixel is assigned an estimated burn date. The final product is delivered in a sinusoidal projection and organized into approximately $10^{\circ} \times 10^{\circ}$ tiles following the MODIS tiling scheme (Giglio et al., 2018). To detect abrupt
110 changes in the time series (pre-fire differences), cumulative maps of aggregated active fires drive the selection of training data for both burned and unburned areas. Burn dates are determined at a 500m grid cell resolution and recorded as the Julian day of the calendar year.

The global burned area datasets employed in this study are available through the Application for Extracting and Exploring Analysis Ready Samples (AppEEARS) (<https://appeears.earthdatacloud.nasa.gov/>, accessed on 15 September 2024) and the
115 Global Wildfire Information System (GWIS) (<https://gwis.jrc.ec.europa.eu/apps/country.profile/downloads>, accessed on 15 September 2024). AppEEARS was used to extract burned area data in netCDF format, enabling spatial and grid-based analysis. In contrast, GWIS provided aggregated statistical data and regional summaries at national and sub-national levels. The data presented in GWIS are based on the Globfire methodology, which employs the MODIS MCD64A1 burned area product to identify wildfire events and calculate the burned area associated with each incident. National burned area totals are derived by
120 aggregating individual fire events. It is important to note that the GWIS GlobFire dataset IS not provided in real time, as the underlying MCD64A1 product becomes available two months after data acquisition. The recorded start and end dates of fire incidents are associated with a temporal uncertainty of a few days.

Land cover type (LCt) analysis was conducted using the MODIS Terra+Aqua MCD12Q1 v061 product obtained from GWIS. These global annual maps (2001–2023) have a 500m resolution and are delivered in HDF4 format.



125 2.4 Methodology

The methodology begins with the collection of two burned area (BA) datasets covering the study period 2002–2023. The analysis focused on burned areas by land cover type (LCt), year, month, and number of fires. Proper alignment of the two datasets was essential for the creation of figures and comparisons.

130 The ability of the MCD64A1 product to capture the spatial and temporal variability of fire events recorded in ground-based data was evaluated using multiple statistical metrics, including ordinary least squares linear regression, the coefficient of determination (R^2), p-value, and percentage difference (error). We calculated the error in annual total burned area as the percentage difference compared to the ground-based data (Galizia et al., 2021), following Eq. (1):

$$\%Diff = 100 \times \frac{|BA_{SB} - BA_{GB}|}{BA_{GB}}, \quad (1)$$

135 where, BA_{SB} represents the annual total burned area detected by MODIS based on MCD64A1 product and BA_{GB} represents the HFS records of annual total BA.

140 For the comparison of BA estimates between MODIS and the HFS, two main land cover categories were defined: Natural and Managed. In the first category, forests and natural vegetation are included, while the second includes agricultural and human-impacted lands. The correspondence in Table 1. is approximate, as land cover categories can be documented in various ways depending on the region and classification system used. These differences introduce uncertainty into the analysis of burned areas.

Table 1. Land cover categorization of MODIS and HFS burned area reports.

Land cover types (LCt)	HFS	MODIS MCD64A1
Natural	Forest	Forest
	Forest Area	Savannas
	Groves	Shrublands-Grasslands
	Grassland	
	Reeds-Marshes	
Managed	Crop Residue	Cropland
	Agricultural Area	Other
	Landfills	

145 For the calculation of the number of fires reported by HFS, fire events were classified into two categories: those with a burned area <21.466 ha and those with $BA \geq 21.466$ hectares (the actual spatial resolution of the MODIS burned area product MCD64A1 is ~ 463 m, meaning that the minimum detectable area is 21.466 ha).



Correlations between ground-based and MODIS MCD64A1 data are assessed using scatter plots. A slope greater than 1 indicates that the MCD64A1 dataset underrepresents fire activity relative to ground-based observations, whereas a slope less than 1 reflects an overrepresentation. A slope equal to 1 denotes full correspondence between the two datasets. The p-value indicates the statistical significance of the relationship observed in the regression analysis. In this study, a low p-value (typically < 0.05) indicates that the observed correlation between MCD64A1 and ground-based fire activity is unlikely to have occurred by chance, supporting the reliability of the regression results.

3 Results and Discussion

3.1 Spatial Accuracy

Both datasets, MODIS MCD64A1 and the Hellenic Fire Service reports, exhibit pronounced interannual variability across all regions, with substantial fluctuations in burned area from year to year. Peak fire activity is observed during 2007, 2021, and 2023. The largest total burned area in Greece is observed in 2007, reaching approximately 313,000 ha based on MODIS estimates, primarily driven by extreme fire activity in the Peloponnese, Western Greece, and Ionian Islands region, contributing approximately 200,000 ha. This is followed by 2023, with an estimated total burned area of around 170,000 ha, with the most extensive impacts recorded in Macedonia and Thrace (~100,000 ha). The third most severe year for Greece is 2021, with total BA reaching about 130,000 ha, mainly associated with large fires in Thessaly and Central Greece (~60,000 ha) and Attica (~20,000 ha).

First, we compare annual total burned area data from MODIS and the Hellenic Fire Service for all years. From 2002 to 2018, there is a systematic underestimation of the burned area by the HFS compared to the MODIS data. Overall, for Greece (Fig. 1a), in 2019 and 2020 the burned area estimates from the two products are relatively close, while for years 2021-2023 the discrepancy is significantly reduced, with the absolute deviation between satellite data and HFS for the years 2021-2023 being 5% on average. The largest discrepancies were observed in Thessaly and Central Greece (Fig. 1d). In contrast, Peloponnese and Western Greece and Ionian Islands (Fig. 1b) show the smallest difference in the burned area estimates, despite having the highest annual totals per year among all regions, with 205,342 ha (MODIS MCD64A1 product) recorded in 2007.



Figure 1. Annual MODIS MCD64A1 and HFS BA (in hectares) for 2002-2023 in Greece (a), as well as by administrative region (b-h). The vertical axis scales vary across panels to enhance the clarity and accurate representation of the temporal trends within each region.

The total burned area for the 21 years reported by MODIS for Greece is about 420,000 ha larger compared to the HFS observations. This discrepancy is primarily attributed to a specific region, i.e. that of Thessaly and Central Greece, where MODIS BA exceeds the HFS's reports by 320,000 ha, and secondarily to Macedonia and Thrace, where the difference amounts to 87,000 ha. Cumulatively for the period 2002–2023, in the Peloponnese, Western Greece, Ionian Islands and the Aegean, the BA reported by both datasets is very close, with deviations between 1 and 3% respectively. The burned area and fire count statistics are summarized in Table 2.



Table 2. Number of fires and total BA in Greece (2002–2023), derived from MODIS observations and HFS records.

Decentralized administration	Number of fires for 2002-2023			Total burned area [ha] for 2002-2023	
	Ground-based BA<21.466ha	Ground-based BA≥21.466ha	MODIS MCD64A1	Ground- based	MODIS MCD64A1
Greece	210,658	2,428	4,004	1,027,948	1,450,535
Peloponnese, Western Greece and Ionian Islands	72,451	502	306	329,159	333,665
Macedonia and Thrace	49,258	320	923	181,199	267,765
Thessaly and Central Greece	40,034	811	2285	257,556	579,192
Attica	4,862	137	62	94,920	105,827
Aegean	10,034	268	102	90,885	87,838
Epirus and Western Macedonia	18,135	249	264	41,330	47,461
Crete	15,884	145	60	32,899	24,042

For the sub-period 2020–2023, the Hellenic Fire Service (HFS) provides point coordinates for each event (annual maps were generated and compared with data, see Supplement Figs. S2–S5), which were compared with MODIS BA product to analyse burned areas by land cover category (see Fig. A1), as summarized in Table 1. We find that, in most cases, MODIS tends to overestimate burned areas in managed land cover types, with the largest discrepancies occurring in Macedonia-Thrace and Thessaly-Central Greece.

Figure 2 shows a fire frequency map which quantifies the number of burn detections per pixel across the complete MODIS burned area record for Greece (2002-2023). Moreover, map extract highlights the highest fire frequency values across the country, which are found in Macedonia and Thrace; Epirus and Western Macedonia; and Thessaly and Central Greece. Specifically, in the prefectures of Thessaly and Central Greece, certain areas are estimated to have burned 13 times during the period 2002–2023. Similarly, in Epirus and Western Macedonia, a specific area was identified with a burning occurrence of 8 times, while a similar occurrence was also observed in Macedonia and Thrace. According to the MODIS landcover product (MCD12Q1.V006), the vegetation type is classified as cropland in these areas.

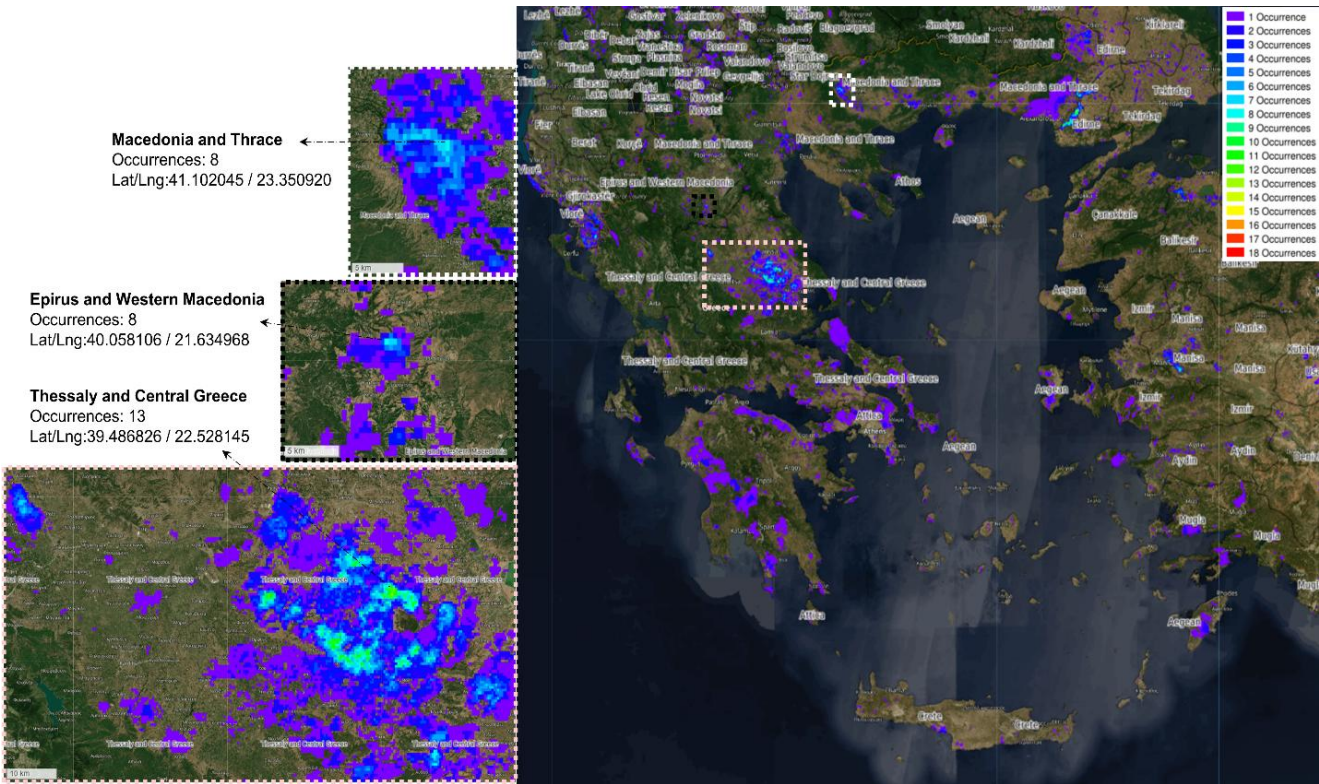


Figure 2. Greece's Fire Frequency from 2002-2023, highlighting the highest occurrence rates in Macedonia and Thrace, Epirus and Western Macedonia and Thessaly and Central Greece. Adapted from the Global Wildfire Information System (GWIS), <https://gwis.jrc.ec.europa.eu>. © European Union, 2020, CC BY 4.0.

The additional detected MODIS burned areas in croplands may originate from deliberate agricultural burning practices or they can stem from surfaces not associated with burning whose spectral properties resemble those of genuinely burned areas. True burned surfaces typically show decreased NIR reflectance due to vegetation removal and increased SWIR reflectance associated with char and exposed soil (Veraverbeke et al., 2011). However, certain agricultural surfaces, such as recently ploughed fields, post-harvest croplands, or areas subjected to residue-burning, often exhibit NIR/SWIR responses comparable to burned soil, resulting in low vegetation-index values (Stroppiana et al., 2012). These spectral similarities have been documented to cause misclassification in the MCD64A1 product, leading to false BA detections even in the absence of wildfire events (Giglio et al., 2018; Boschetti et al., 2019). It is important to note that such land management activities are not recorded by the HFS, as they do not require operational response. This issue is further exacerbated by the coarse spatial resolution of MODIS, which studies have shown to produce both omission and commission errors depending on landscape heterogeneity and the size of burned patches (Padilla et al., 2015; Giglio et al., 2018; Boschetti et al., 2019).

Table 3. Percentage difference between the estimates of MODIS and the HFS archives for Greece and its regions, considering all land cover types and natural-only LCt separately (2002–2023).



Decentralized Administrations	Land Cover type (LCt)	%Diff
Greece	All	41%
	Nat.	12%
Peloponnese and Western Greece and Ionian Islands	All	1%
	Nat.	30%
Macedonia and Thrace	All	48%
	Nat.	15%
Thessaly and Central Greece	All	66%
	Nat.	51%
Attica	All	20%
	Nat.	31%
Aegean	All	3%
	Nat.	8%
Epirus and Western Macedonia	All	15%
	Nat.	47%
Crete	All	27%
	Nat.	25%

When quantitatively assessing difference, we find that on the national scale, MODIS overestimates burned area by 41% when
 215 all LCt are included, while the difference drops to 12% for natural LCt only. The largest discrepancies occur in Thessaly and
 Central Greece, with %Diff reaching 66% (All LCt) and 51% (Nat.). In contrast, Attica, Crete, and Epirus and Western
 Macedonia which are the regions with the lowest detected BA, show moderate to high discrepancies, particularly for natural
 LCt. Overall, the results indicate substantial spatial variability in MODIS–HFS agreement, with improved consistency when
 the analysis is restricted to natural LCt.

220 3.2 Temporal Accuracy

Temporal agreement is assessed by examining the seasonality of burned area by region in Greece for the period 2002–2023,
 separately for all (solid line) and for natural LCt (dashed line). Regarding natural LCt, as shown by the dashed lines in Fig. 4,
 the estimates between MODIS and the HFS are more consistent in most of the decentralized administrations.

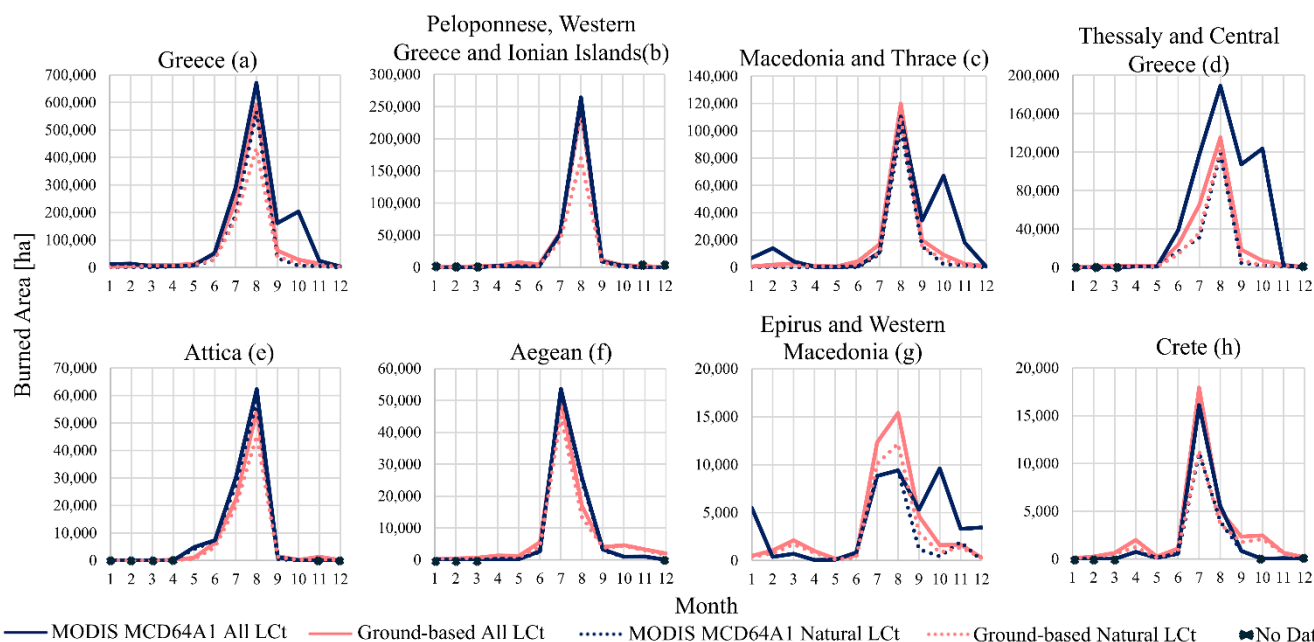


Figure 3. Seasonality of the fire statistics in Greece and by decentralized administration for 2002-2023, across all and natural Land Cover types (LCt) separately. The vertical axis scales vary across panels to enhance the clarity and accurate representation of the temporal trends within each region.

In Fig. 3. for all LCt, the largest differences in burned area for Greece overall (Fig. 3a solid line) are found for September and October, with MODIS exhibiting substantial overestimation. This overestimation is mainly driven by Macedonia and Thrace (Fig. 3c), Thessaly and Central Greece (Fig. 3d), and Epirus and Western Macedonia (Fig. 3g). In contrast, MODIS underestimates BA in Crete (Fig. 3h), and the Aegean Islands (Fig. 3f). In Epirus and Western Macedonia, MODIS tends to underestimate BA during July and August, while it overestimates from September to January.

When the managed LCt is removed, the agreement between datasets improves significantly. For Greece as a whole (Fig. 3a dashed line), the only remaining MODIS overestimation (though smaller) appears in August, primarily due to contributions from the Peloponnese, Western Greece and Ionian Islands and Attica. In Epirus and Western Macedonia, the previously observed discrepancies are largely reduced.

The seasonal overestimation of MODIS burned area during September and October, concentrated in northern and central Greece, is consistent with known algorithm limitations in heterogeneous landscapes with significant agricultural activity (Giglio et al., 2018). Potential sources of commission errors in satellite-based burned area detection include, among others, agricultural practices, image pixel size, and the land-cover mask adopted to minimize false alarms (Laneve et al., 2024). The MCD64A1 C6 algorithm doubles reported cropland burned area relative to its predecessor in several regions, with a portion of this additional mapped area likely attributable to commission errors from tiling and harvesting rather than actual burning (Giglio et al., 2018; Hall et al., 2021). The substantial improvement in dataset agreement after removing the managed land cover type confirms that agricultural burning is a primary driver of MODIS overestimation in these regions. The contrasting



underestimation in Crete and the Aegean Islands reflects the relationship between fire size, landscape fragmentation, and MODIS detection capability. MCD64A1 C6 has less than 50% detection probability for fires in the 10–100 ha range, with performance improving substantially only for fires exceeding 100 ha in forest and semi-natural area (Katagis and Gitas, 2022). The relationship between annual ground-based and MODIS BA [ha] was evaluated using Ordinary Least Squares (OLS) linear regression. The R^2 statistic was used to evaluate model fit, and the p-value determined the statistical significance of the regression. The results are presented in Fig. 4 for each administration.

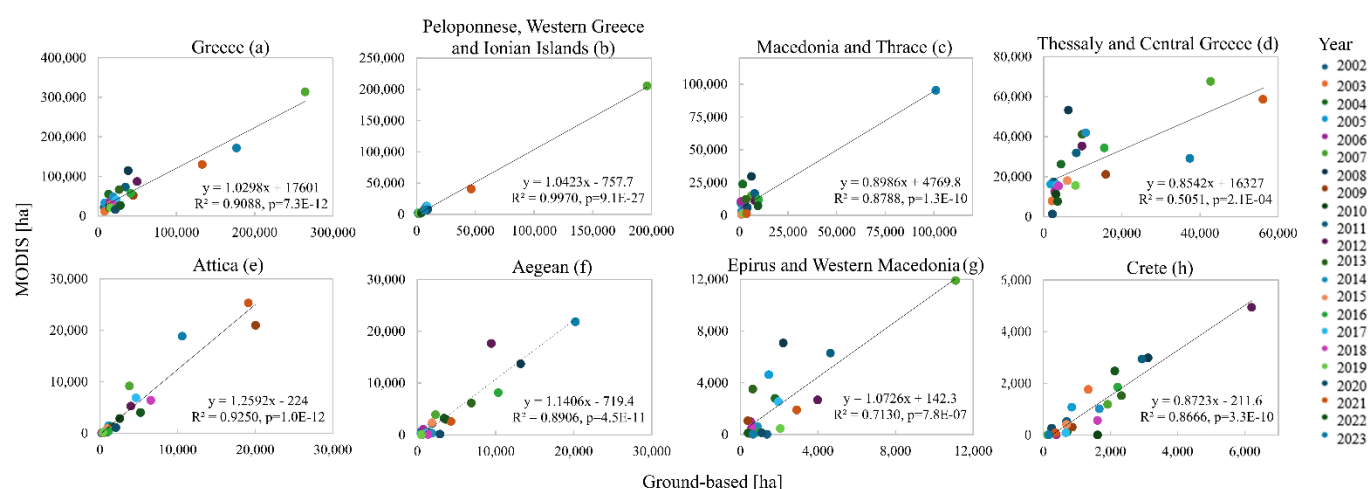


Figure 4. Annual comparison of ground-based and MODIS BA [ha], for each region within Greece. Different colours indicate different years from 2002 to 2023. The vertical axis scales vary across panels to enhance the clarity and accurate representation of the temporal trends within each region.

The analysis reveals highly significant results with low p-values, the highest of which is found for Thessaly and Central Greece at 2.1×10^{-04} (<0.05) (Fig 4d). There is overwhelming statistical evidence to conclude that the observed effect is genuine and not attributable to random chance across the corresponding comparison. In five out of seven areas, the coefficient of determination R^2 is greater than 0.8666. The high correlation and strong linear relationship between the two datasets indicate that the satellite and the Fire Agency provide comparable BA estimates. The Peloponnese and Western Greece and Ionian Islands region have the highest R^2 (Fig. 4b), indicating an almost perfect linear relationship between the datasets. Figure 4 shows that the largest deviation from MODIS, exceeding the HFS data occurs in 2008 across Greece as a whole, mainly due to Thessaly and Central Greece and Epirus and Western Macedonia. Thessaly and Central Greece and Epirus and Western Macedonia exhibit a wider spread of points around the regression line, suggesting a greater discrepancy in the data. Our analysis shows a strong linear relationship for time series with years featuring extreme fire activity, aligning with previous assessments of European fire regimes (European Commission Joint Research Centre, 2020). This suggests that while MODIS tends to underestimate the total number of fires, it effectively captures the majority of the total burned area during extreme events, as large fires account for most biomass consumption (Randerson et al., 2012).



Finally, the dataset agreement was assessed through an evaluation of the fire size distribution, specifically by examining the fire frequency per size class and the percentage contribution of each class to the overall burned area as shown in Figure 5.

Figure 5 shows the number of fires within each fire-size class, ranging from 0–32 ha to 8,192–16,384 ha. Lines representing MODIS and Fire Service data, respectively, indicate the contribution of each fire-size class to the total BA.

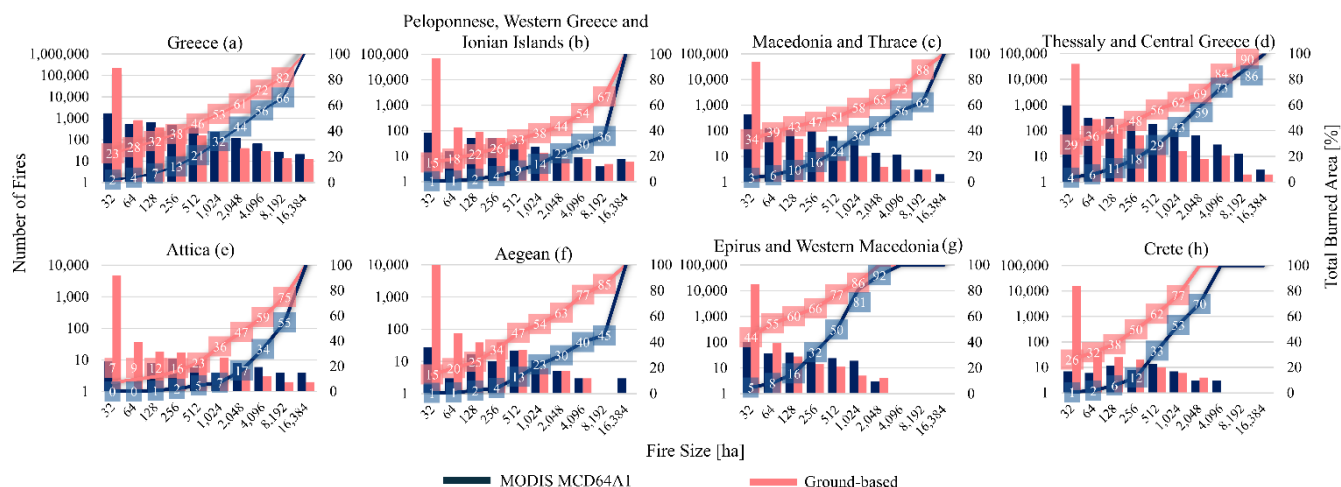


Figure 5. Fire size dynamics and % contribution to total burned area in Greece and within Greek regions, for the HFS and MODIS MCD64A1 datasets for 2002-2023. Bars showing the number of fires in a fire size class interval using a logarithmic scale (base 10) (left vertical axis). Lines showing the percentage contribution of fire class to the cumulative burned area (right vertical axis). The exact BA percentage for each class is reported above each diagram. Fire size [ha] is presented on the horizontal axis on a logarithmic scale with base 2, consistent with GWIS MODIS statistical charts for fire size distribution and % contribution to the total burnt area. The vertical axis scales vary across panels to enhance the clarity and accurate representation of the temporal trends within each region.

Higher contribution percentages are observed in the Fire Service records for almost every size class. The results indicates that the majority of fires reported by ground-based sources are small (0-32 ha), with a more even distribution across various fire size categories. Fire Service records include numerous minor events below the MODIS detection threshold. In most cases, MODIS detects fewer smaller fires than the Fire Service but demonstrates stronger agreement for larger fires. The ground-based line follows a trend similar to that of the MCD64A1 product. For this reason, in several areas MODIS reports a higher percentage of burned area (BA) for the larger fire-size classes (≥ 4096 ha) compared to Fire Service records, suggesting that some large fires may be underestimated in the ground-based data. As expected, the number of fires decreases with increasing fire size, however, the contribution of these large fires to the total burned area is high.

Our results corroborate validation studies showing that satellite-based BA products such as MCD64A1 systematically under-detect small fires (< 100 ha), particularly in Mediterranean ecosystems (Katagis and Gitas, 2022). Although the MODIS product captures large and catastrophic wildfire events, it misses the small-scale activity defining the Mediterranean fire regime, reinforcing the fire-size detection bias reported by Turco et al. (2019). The strong inter-annual agreement between MODIS and HFS data is consistent with previous assessments of satellite burned area products in Mediterranean Europe, which found high temporal correlation between MODIS and ground-based datasets (Turco et al., 2019; Galizia et al., 2021),



and with studies documenting the extreme fire activity in Southern Europe during 2007 (Koutsias et al., 2013; Trigo et al., 2013). Finally, a recent global validation study by Giglio et al. (2025) indicates that even newer generation products, such as the NASA VIIRS burned area dataset (VNP64A1), exhibit omission and commission errors comparable to those of MODIS. This suggests that despite algorithmic advances, the physical constraints of spatial resolution, orbital overpass timing, and atmospheric interference remain the primary barriers to accurate global burned area mapping.

4 Conclusion

This study provides a comprehensive comparative assessment of MODIS MCD64A1 satellite observations and Hellenic Fire Service (HFS) ground records for Greece over a 22-year period (2002–2023). The analysis demonstrates the capabilities and limitations of satellite-based and ground-based monitoring, illustrating the complementary value of integrating such observations. The results reveal a very good overall agreement, although significant divergence exists in total burned area estimates, with MODIS exceeding HFS records by approximately 420,000 ha cumulatively over the entire study period. This discrepancy is concentrated primarily in Thessaly-Central Greece, and Macedonia-Thrace, particularly outside the summer fire season. The two datasets show strong overall agreement in capturing inter-annual fire variability ($R^2 > 0.87$ in five of seven regions), with particularly close correspondence during extreme fire years such as 2007, 2021, and 2023. Agreement has improved notably in recent years, with absolute deviation averaging just 5% over 2021–2023.

Despite this consistency in temporal variability, systematic differences remain in total burned area estimates. MODIS overestimates national burned area by 41% when all land cover types are considered, primarily due to cropland detections in Thessaly-Central Greece, and Macedonia–Thrace. Notably, Thessaly and Central Greece, which exhibited the largest discrepancy between the datasets when all land cover types were included, shifts to having the second lowest discrepancy after excluding managed land cover types. Seasonally, MODIS overestimation is most pronounced in September and October across northern and central Greece, while it systematically underestimates burned area in Crete and the Aegean Islands, likely due to small-scale fires falling below the 500 m detection threshold and differences in burned land cover classification. MODIS also underestimates the total count of fire events, yet captures the bulk of total burned area because large fires dominate cumulative BA.

MODIS proves reliable in monitoring extreme fire seasons (e.g., 2007) and capturing the extent of large-scale events. However, it demonstrates limited capability in detecting small-scale fires. Conversely, while HFS data provides detailed records of small ignition events, they tend to underestimate the spatial extent of major wildfires. These findings underline the importance of integrating both satellite and field data for comprehensive wildfire monitoring. Understanding their respective strengths and weaknesses supports more accurate fire assessments, enhances response planning, and contributes to more effective fire management policies. Future research that incorporates high-quality ground-based fire data from regions with diverse fire regimes could shed important light on the uncertainties found in remote sensing fire products.



Appendix A

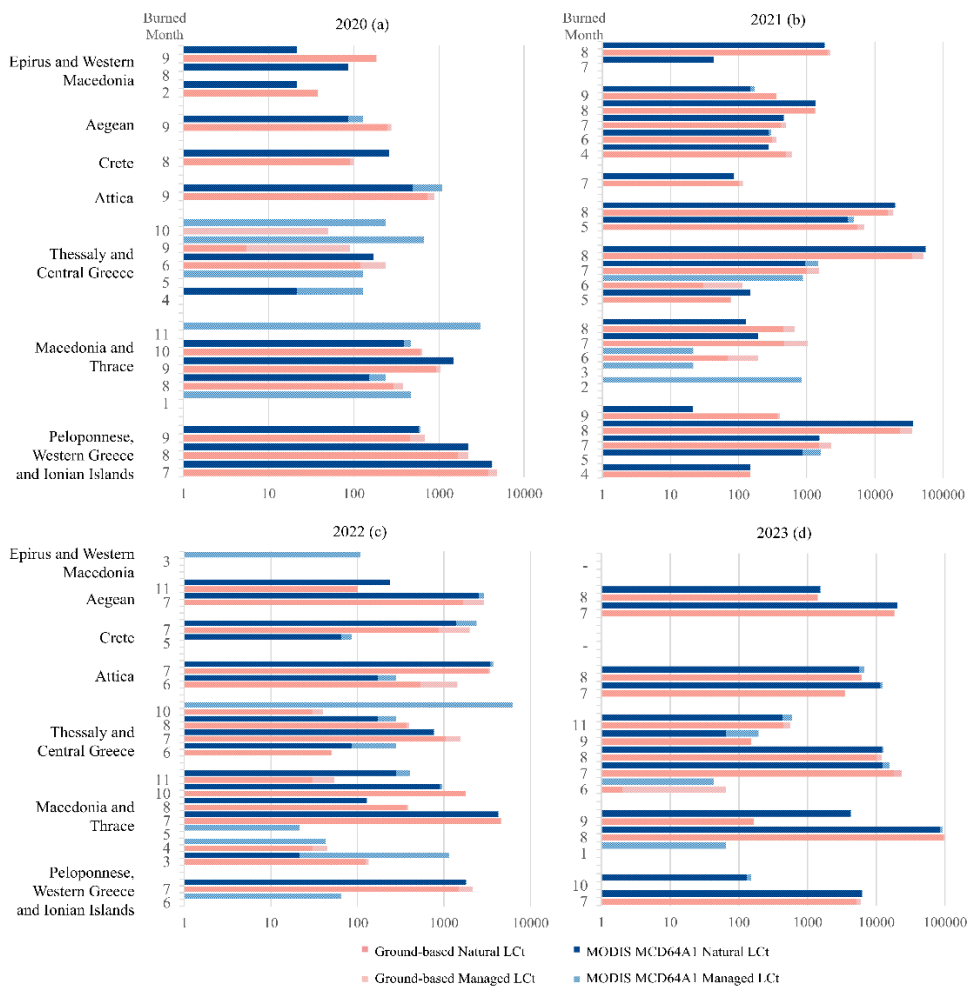


Figure A1. Comparative analysis of fire activity and land cover distribution in Greece based on MODIS MCD64A1 product and ground-based records from HFS. X-axis represents the burned area in hectares on a logarithmic scale to enhance the clarity of fire size distribution. The y-axis corresponds to the month in which a fire was detected based on MODIS data, for each decentralized administration in Greece. Each diagram shows monthly burn detections for 2020 (a), 2021 (b), 2022 (c), and 2023 (d).

Data availability

The ground-based fire records are openly accessible through the official Hellenic Fire Service site at https://www.fireservice.gr/el_GR/synola-dedomenon (last access: 10 September 2024).

Ssatellite-derived MODIS MCD64A1 burned area product used in this study are public available from the Global Wildfire Information System (GWIS; Joint Research Centre, 2020) at <https://gwis.jrc.ec.europa.eu/apps/country.profile/downloads> (last access: 30 September 2024).



Author contributions

CZ: Data curation, Formal analysis, Investigation, Methodology, Visualization, Original draft preparation; MG: Methodology, Co-supervision, Writing review & editing; AV: Conceptualization, Methodology, Supervision, Validation, Writing, review & editing.

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Competing interests

The authors declare that they have no conflict of interest.

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