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Spatiotemporal Analysis of Forest Fires in Cyprus Using Earth Observation and Climate Data †

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Abstract

Wildfire detection remains a critical challenge for authorities, with human activity being the leading cause. The historical conditions prevailing in burned forest areas require a comprehensive analysis at both the environmental and anthropogenic levels. This study presents a multidimensional dataset comprising data from 2008 to 2024 and integrating Earth observation data and anthropogenic, environmental, meteorological, topographic, and fire-related features. This study evaluates, through time series analysis, the impact of climate trends such as increased temperature in comparison with anthropogenic activities such as deliberate fires. Time series analysis reveals that although climatic conditions with increased temperature and reduced precipitation in Cyprus intensify the risk of fire, the presence of fire events is primarily due to deliberate actions. The findings of this study support national-scale fire modeling, offering a foundation for targeted prevention, early warning systems, and sustainable forest fire management strategies.

Keywords: wildfire risk prediction; time series analysis; machine learning; Earth observation; Cyprus

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1. Introduction

Wildfires are a persistent and escalating threat in all ecosystems but are particularly characteristic of the Mediterranean region [1]. Extreme weather conditions characterized by increasing heatwaves combined with drought and land-use change are expected to lead to highly flammable environments, leading to higher fire risk, longer fire seasons, and more frequent large and severe fires [2–4]. Additionally, the impact of wildfires on society has increased due to factors like urban expansion [5] into fire-prone zones, human-caused fires in unadapted ecosystems, and the accumulation of combustible material (fuel), which can lead to uncontrollable mega-fires [6,7]. It is worth mentioning that these fires result from fuel accumulation during the wet season and increased drought during the dry summer season.

Time series analysis has historically served as a fundamental element that provides scholars with a means to scrutinize patterns and developments evident in longitudinal data. Such methodology proves indispensable in deciphering fluctuations across seasons, extended alterations, and prospective trajectories [8]. The efficacy of machine learning is significantly enhanced through its application to multimodal datasets that fuse data from various sources and types. Such datasets facilitate a more holistic understanding of complex systems through the integration of disparate information, including satellite imagery, ground-based measurements, and socio-economic data [9].

The integration of time series analysis, spatiotemporal methods, machine learning, and multimodal datasets has significantly advanced environmental research, particularly in wildfire risk prediction and management. These combined approaches offer powerful tools for understanding complex dynamics and improving forecasting accuracy [10–13] supporting more informed decision-making in wildfire mitigation and broader environmental challenges.

Evaluating the integrated spatiotemporal patterns of natural hazardous events is crucial for effective disaster risk management [12–15]. This study aims to conduct a comprehensive spatiotemporal analysis of forest fires in Cyprus, located in the Eastern Mediterranean region, utilizing a multimodal dataset. It specifically seeks to understand the environmental conditions, such as temperature, humidity, and wind speed, that contributed to the occurrence of fire events during the period from 2008 to 2024 in order to provide data-driven insights that support fire prevention strategies. For the purposes of this study, the methodology is divided into two main parts: the first focuses on developing the multimodal dataset, and the second on spatiotemporal analysis.

Regarding the spatiotemporal analysis of fires occurrences similar studies were conducted in several parts of the world like Australia [16], Brazilian Amazon [17], Spain [18], Portugal [14], Southern Africa [19], Africa and Madagascar [20] and Mediterranean Basis [21].

2. Methodology

2.1. Study Area

Cyprus is located at the northeastern end of the Mediterranean basin, covering an area of 9251 Km^2. The island features a predominantly mountainous terrain and a distinctly Mediterranean climate, characterized by dry and hot summers that typically extend from May to October. During the fire season, temperatures range from 30 °C to 40 °C, increasing the risk of ignition. Relative humidity also plays a crucial role in the fire dynamics, varying from 30% to 65%. Precipitation during this period is very low, generally ranging between 0 and 50 mm. Wind is another significant factor; during the fire season, it is generally northwesterly or northerly. Wind greatly impacts fire behavior and poses challenges to prediction due to its variability in speed and direction, along with the influences from topography, vegetation, and local conditions [22–25].

Based on the records provided by the Department of Forests in Cyprus from 2000 to 2023 (Figure 1), forest fires (of which 37.2% attributed to human activities) in Cyprus destroyed over 55,240 ha of burnt areas, including state forests and surrounding areas [26].

2.2. Data and Methods

Data Processing

This study focuses on the spatiotemporal analysis of peak fire occurrence during summer periods (June–August). The analysis was conducted over a 17-year period, from 2008 to 2024, using a multimodal EO dataset. Specifically, data from various sources were used to create the multidimensional dataset for the analysis of fires in Cyprus based on the approach conducted by Prodromou et al., 2024 [27]. Table 1 summarizes all the data collected from the respective sources, including some information on their spatial and temporal analysis.

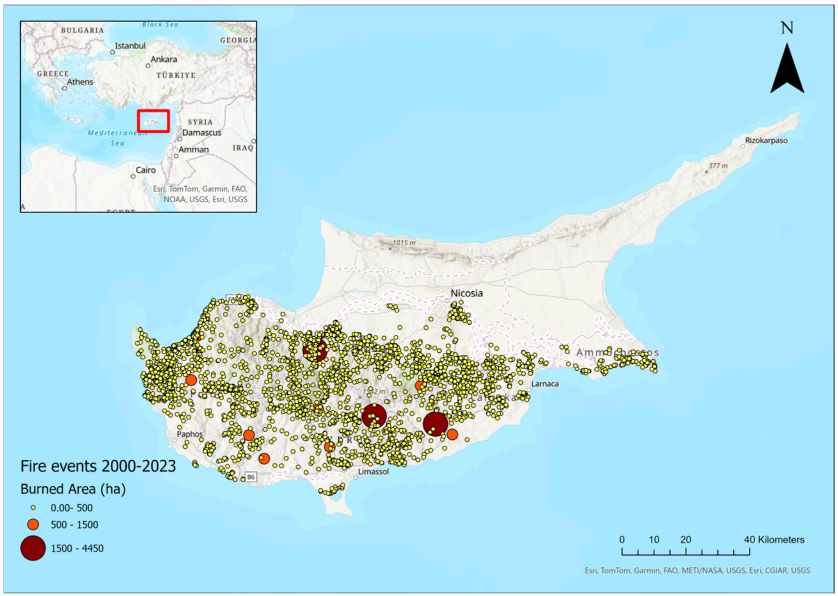

Figure 1. Forest fires in Cyprus from 2000 to 2023, based on the statistics provided by the Department of Forests in Cyprus.

Table 1. Overview of the data sources, spatial and temporal resolution, and variables used for fire occurrence analysis.

Source	Feature	Spatial Resolution	Temporal Resolution
MODIS	Land Surface Temperature (MYD11A2 and MOD11A2)	1 km	8 days
	NDVI, EVI (MYD13A1 and MOD13A1)	500 m	16 days
ERA 5—reanalysis	2 m temperature, 2 m dewpoint temperature, and Total Precipitation	9 km	hourly
	10 m U and V wind component; Wind speed and direction (dirmax, domra)		
Land—Copernicus	Corine Land Cover	2012, 2018	100 m
	Digital Elevation Model (DEM) (slope, elevation, aspect)		25 m
EFFIS	Fire history	daily 2009–2022	20–250 m
Datagov.cy	Anthropogenic factors—Picnic, camping areas, and deliberate fires	Static	-

Time series analysis was applied to the abovementioned environmental variables in order to investigate the seasonal dynamics in Cyprus, followed by correlation analysis using the Pearson correlation coefficient that was employed to examine the relationships between fire occurrence and its potential drivers. This integrated approach supports a comprehensive understanding of the spatiotemporal variability and underlying drivers of wildfire activity.

Also, the Random Forest classifier was implemented for this study to predict the fire risk. Prior to implementing the algorithm, some pre-processed actions were applied to the dataset to address missing values (NaN) and normalize features to a common scale to ensure consistent performance across different data types. Hyperparameter tuning was conducted using the RandomizedSearchCV approach, and model robustness was ensured through GroupKFold cross-validation. Various metrics, including precision, recall, F1-score, and AUC, were employed to assess model accuracy during tuning.

3. Results and Discussion

Based on the analysis of the annual variation in fire frequency in the Cyprus region during the summer months from 2008 to 2024, the results present a moderate increasing trend, as shown in Figure 2, with an average annual increase of 8.5 hectares. However, the low R^2 (0.12) indicates high interannual variability, suggesting that fire activity is driven by complex, non-linear environmental and anthropogenic factors.

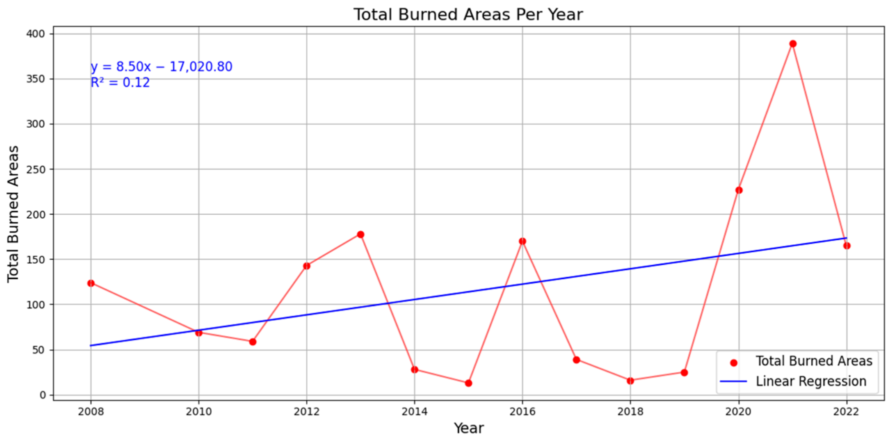

Figure 2. Linear trend analysis for total burned area per year.

Based on the Pearson correlation (Figure 3), a strong positive relationship was indicated between temperature-related variables (e.g., max, mean, and dew point temperatures), indicating their independence. In addition to that, vegetation indices (EVI and NDVI) also showed strong correlation, reflecting consistent vegetation dynamics. Fire occurrence shows weak to moderate positive correlations with variables such as maximum temperature and NDVI and negative correlations with precipitation and nighttime land surface temperature. These results underscore the importance of investigating various fire-related variables to comprehend fire dynamics.

Subsequently, boxplot analysis explored the distribution of the values for key environmental variables in cases of fire occurrence and non-fire occurrence as presented in Figure 4. The outcomes revealed that areas affected by fire consistently exhibited higher values of temperature-related variables, including mean air temperature, daytime land surface temperature, and nighttime temperature, compared to non-fire areas. These findings underline the role of heat stress in promoting fire occurrence. In addition, fire-prone areas showed slightly higher vegetation indices (NDVI, EVI), suggesting that greater vegetation biomass may contribute to higher fuel availability. Notably, total precipitation values were low in both fire and non-fire areas; however, fire-affected zones exhibited slightly lower median values and a narrower range, indicating consistently drier conditions that may contribute to fire ignition and spread. The topographic characteristics, i.e., elevation showed moderate differences, where fire events were observed more frequently at lower altitudes. These patterns highlight the correlation between climatic stressors, vegetation structure, and terrain in shaping wildfire susceptibility.

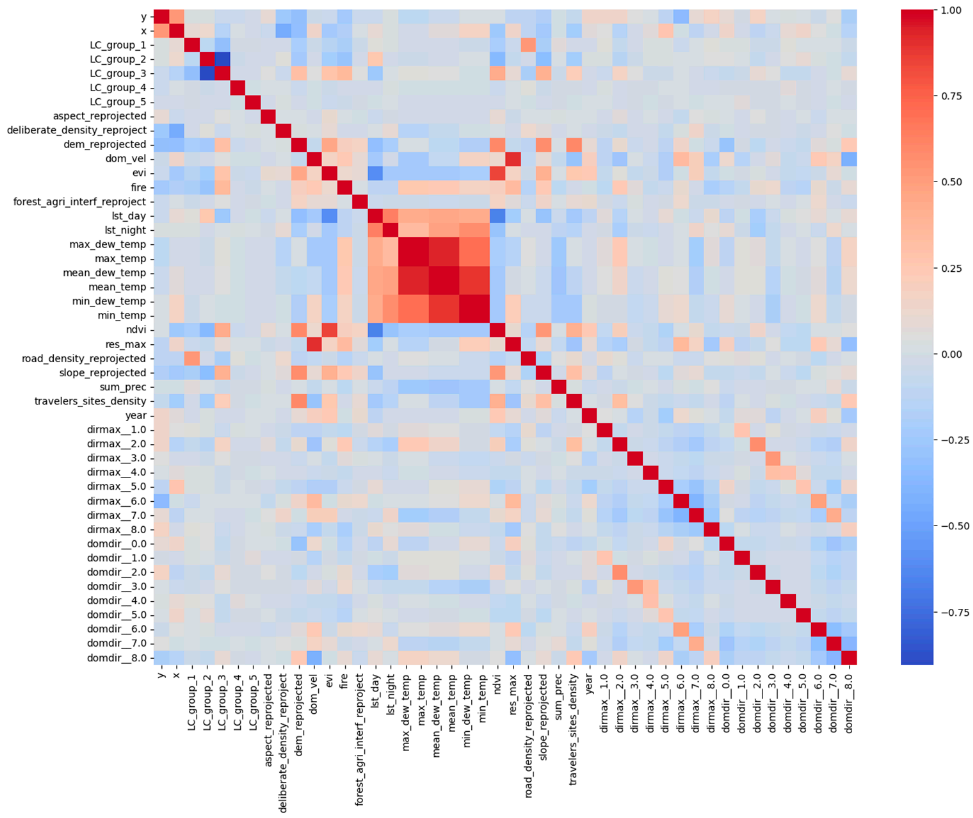

Figure 3. Pearson correlation matrix of the variables included in the multimodal dataset.

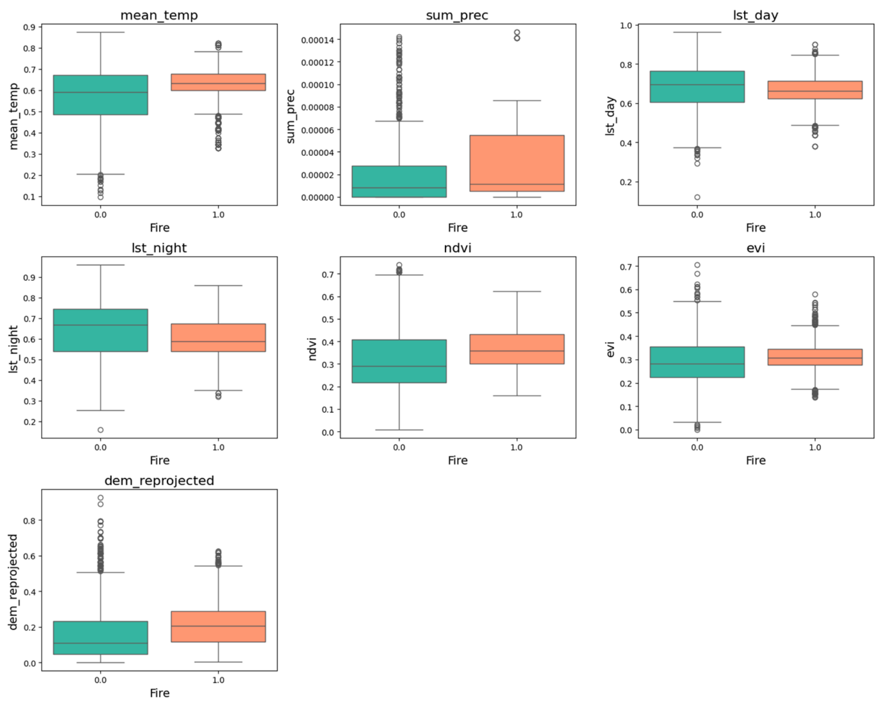

Figure 4. Boxplots comparing the distribution of key environmental variables between fire-affected (fire = 1) and non-fire (fire = 0) locations.

Furthermore, a machine learning-based fire risk prediction model was developed using the built multimodal dataset. Among the tested classifiers, the Random Forest algorithm exhibited strong predictive capabilities, especially when evaluated against a GroupKFold cross-validation approach. Following hyperparameter optimization using

RandomizedSearchCV, the Random Forest classifier achieved a recall of 100% for fire events and 74% for no-fire instances on the test set, demonstrating its suitability for operational use as presented in Figure 5.

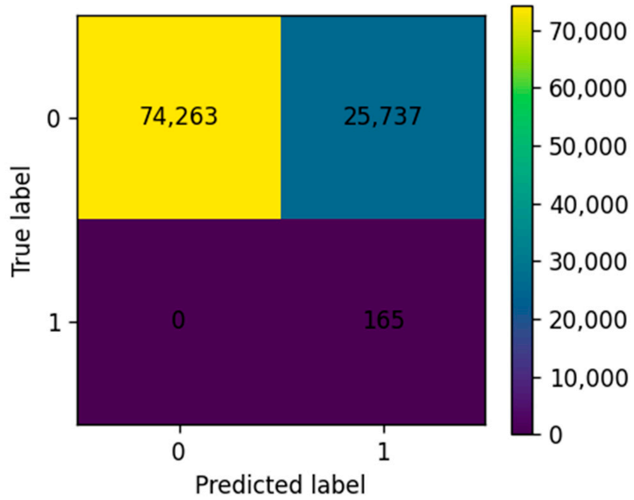

Figure 5. Confusion matrix for the Random Forest classifier.

4. Conclusions

This study presents a comprehensive approach to the spatiotemporal analysis of wildfire risk in Cyprus by integrating environmental, climatic, and anthropogenic variables into a harmonized multimodal dataset. Based on the findings derived from the spatiotemporal analysis, the climatic variables like high temperature and low precipitation lead to the increase of fire susceptibility, but in our case, human activities and especially deliberate fires correspond to the main ignition cause. Moreover, the time series analysis from 2008 to 2024 indicated that precipitation showed a stronger inverse relationship with burned areas than temperature, highlighting the importance of dry conditions. Regarding the machine learning algorithm, the Random Forest classifier trained on this dataset achieved 100% recall for fire events, demonstrating high potential for operational fire prediction. These findings support the use of AI and multimodal data fusion for developing early warning systems and future digital twin models to enhance wildfire management in the Eastern Mediterranean. Our future work will focus on a comparative analysis of machine learning and deep learning algorithms to enhance fire risk prediction capabilities in Cyprus.

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