



# Interpretable Machine Learning-Based Wildfire Susceptibility Mapping in a Mediterranean Landscape: The Muğla Case <sup>†</sup>

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## Abstract

Extreme wildfire events are increasingly shaping Mediterranean fire regimes under the combined influence of climatic variability, vegetation stress, and growing anthropogenic pressure, posing critical risks to ecosystem stability and landscape resilience. Understanding the spatial determinants of wildfire susceptibility is therefore essential for advancing evidence-based fire risk assessment in fire-prone Mediterranean environments. This on-going doctoral research investigates the environmental controls of wildfire occurrence in Muğla Province (Türkiye) through the integration of multi-source remote sensing data, geospatial analysis, and interpretable machine learning techniques. Burned-area reference data for 2021–2024 were derived from the MODIS MCD64A1 product within the Google Earth Engine environment and represented using a binary burned/non-burned classification. Predictor variables include ERA5-Land meteorological indicators, SRTM-derived topographic parameters, MODIS-based NDVI vegetation condition, and WorldPop population density as a proxy for human exposure, harmonized at a common 1 km spatial resolution. A Random Forest model was implemented to examine wildfire susceptibility patterns with emphasis on model interpretability and variable contribution rather than predictive optimization. Preliminary results indicate that vegetation condition, wind-related dynamics, and population density are dominant contributors to wildfire occurrence, reflecting coupled ecological vulnerability and human influence. Extreme fire conditions observed during 2021 are intentionally reserved for subsequent validation and stress-testing analyses. The proposed framework provides a transparent and transferable methodological basis for analyzing extreme wildfire susceptibility in Mediterranean landscapes and supports future development of interpretable, data-driven wildfire risk assessment approaches.

**Keywords:** wildfire susceptibility; Random Forest; Google Earth Engine; Mediterranean ecosystems; remote sensing; interpretable machine learning; Muğla



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## 1. Introduction

Mediterranean and Mediterranean-type ecosystems are experiencing a pronounced transformation in wildfire regimes, characterized by increasing frequency, magnitude, and severity of extreme wildfire events (EWEs) driven by climatic warming, prolonged drought, vegetation stress, and expanding anthropogenic pressure [1–3]. Intensifying atmospheric aridity, recurrent heatwaves reduce fuel moisture and promote hazardous fire-weather

conditions that exceed historical suppression capacity [2]. Beyond meteorological controls, wildfire susceptibility is increasingly shaped by land-use transitions, human accessibility, and spatial settlement patterns, producing compound landscape vulnerability [3–7]. These dynamics highlight the need for spatially explicit and process-informed wildfire-risk assessment frameworks capable of capturing interactions among climate, vegetation, and human activity.

Advances in remote sensing, Geographic Information Systems, and machine learning modeling have substantially improved the ability to characterize wildfire susceptibility across multiple scales. However, many high-performing models remain difficult to interpret, limiting their usefulness for decision-support. This study addresses that gap by implementing an interpretable Random Forest framework to identify dominant environmental drivers of wildfire occurrence in Muğla Province, a Mediterranean region strongly affected by the extreme 2021 fire season.

Unlike conventional Random Forest-based susceptibility studies primarily focused on predictive optimization, the proposed framework emphasizes interpretability, temporal separation, methodological transparency, and extreme-event robustness by excluding the catastrophic 2021 wildfire season from model training. The framework additionally emphasizes methodological transparency and future extreme-event generalization rather than purely predictive optimization.

2. Study Area and Data

This study focuses on Muğla Province in southwestern Türkiye, characterized by hot dry summers, complex topography, and extensive forested ecosystems highly susceptible to wildfire occurrence. Burned-area data for 2021–2024 were derived from the MODIS MCD64A1 product using Google Earth Engine. Annual burned-area statistics are summarized in Table 1. Environmental predictors included ERA5-Land meteorological variables, SRTM-derived topographic parameters (elevation, slope, aspect), MODIS NDVI vegetation condition, and WorldPop population density. All datasets were harmonized to a common 1 km spatial resolution. A common 1 km spatial resolution was selected to harmonize heterogeneous environmental datasets with differing native resolutions while maintaining regional-scale computational feasibility and consistency with MODIS-derived wildfire products. A common 1-km spatial resolution was selected to harmonize heterogeneous environmental datasets with differing native resolutions while maintaining regional-scale computational feasibility and consistency with MODIS-derived wildfire products (Table 2).

Table 1. Annual burned-pixel counts and approximate burned-area estimates derived from MODIS MCD64A1 for Muğla Province (2021–2024).

| Year | Burned Pixels | Approximate Burned Area (km <sup>2</sup> ) |
|------|---------------|--------------------------------------------|
| 2021 | 706           | ~706                                       |
| 2022 | 92            | ~92                                        |
| 2023 | 9             | ~9                                         |
| 2024 | 21            | ~21                                        |

Burned-area estimates were approximated using 1 km spatial aggregation of MODIS burned pixels.

Table 2. Environmental variables and data sources used in the wildfire susceptibility framework.

| Variable Category | Variable         | Data Source | Native Resolution | Harmonized Resolution |
|-------------------|------------------|-------------|-------------------|-----------------------|
| Meteorological    | Air Temperature  | ERA5-Land   | ~9 km             | 1 km                  |
| Meteorological    | Precipitation    | ERA5-Land   | ~9 km             | 1 km                  |
| Meteorological    | Wind u-component | ERA5-Land   | ~9 km             | 1 km                  |

Table 2. Cont.

| Variable Category | Variable           | Data Source   | Native Resolution | Harmonized Resolution |
|-------------------|--------------------|---------------|-------------------|-----------------------|
| Meteorological    | Humidity proxy     | ERA5-Land     | ~9 km             | 1 km                  |
| Meteorological    | Surface pressure   | ERA5-Land     | ~9 km             | 1 km                  |
| Vegetation        | NDVI               | MODIS         | 250–500 m         | 1 km                  |
| Topographic       | Elevation          | SRTM DEM      | 30 m              | 1 km                  |
| Topographic       | Slope              | SRTM DEM      | 30 m              | 1 km                  |
| Topographic       | Aspect             | SRTM DEM      | 30 m              | 1 km                  |
| Anthropogenic     | Population density | WorldPop      | 1 km              | 1 km                  |
| Target variable   | Burned area        | MODIS MCD64A1 | 500 m             | 1 km                  |

All datasets were spatially harmonized in Google Earth Engine using EPSG:4326 projection at a common 1 km spatial resolution.

3. Methods

Wildfire susceptibility was modeled using a Random Forest classifier implemented in Python 3.12.13 (scikit-learn). The model was designed to prioritize interpretability and environmental driver identification rather than predictive optimization. To avoid bias from extreme conditions, the 2021 wildfire season was excluded from model training and reserved for independent validation and stress-testing. Model development used 2022–2024 data, and variable-importance analysis was applied to identify dominant controls on wildfire occurrence. The final labeled dataset consisted of 610 burned and 4184 non-burned samples derived from the 2022–2024 period (Table 3). Burned pixels were defined using the BurnDate > 0 condition from the MODIS MCD64A1 product, and samples were labeled as burned or non-burned prior to predictor extraction. The 2021 wildfire season was intentionally excluded from model training due to its anomalously high burned-area extent relative to subsequent years.

Table 3. Sampling summary and dataset structure.

| Dataset Component       | Description                                          |
|-------------------------|------------------------------------------------------|
| Burned-pixel definition | BurnDate > 0                                         |
| Label structure         | Binary burned/non-burned                             |
| Burned samples          | 610                                                  |
| Non-burned samples      | 4184                                                 |
| Total samples           | 4794                                                 |
| Training period         | 2022–2024                                            |
| Validation strategy     | 2021 extreme wildfire season reserved for validation |
| Spatial resolution      | 1 km                                                 |
| Burned-pixel definition | BurnDate > 0                                         |
| Label structure         | Binary burned/non-burned                             |

All datasets were spatially harmonized in Google Earth Engine using EPSG:4326.

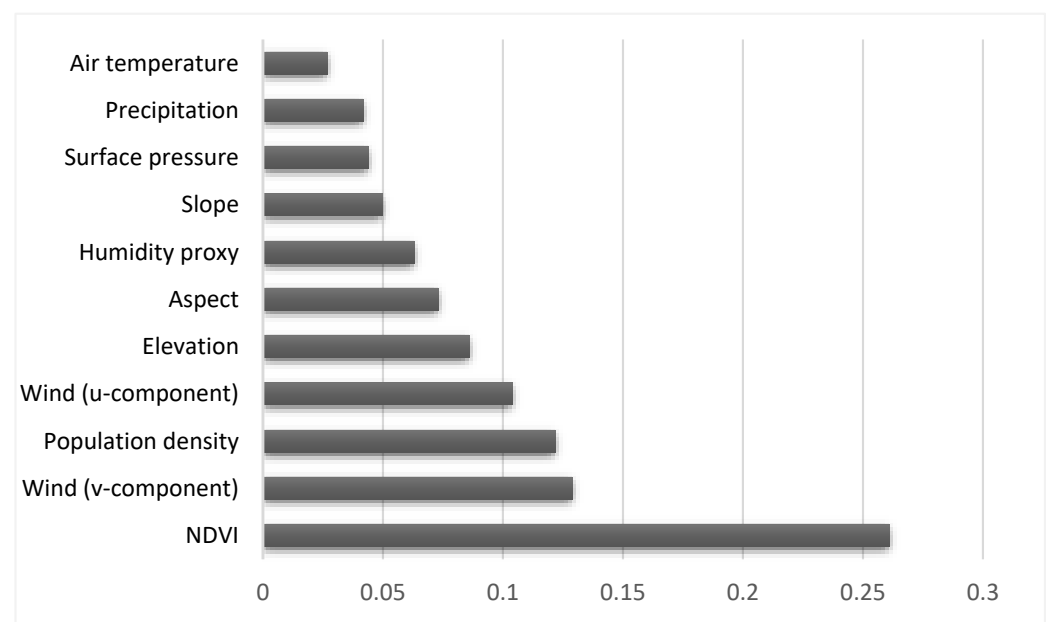
4. Results and Discussion

Burned-area analysis revealed strong interannual variability, with 2021 representing an extreme wildfire year. The Random Forest model demonstrated strong discrimination between burned and non-burned conditions (ROC–AUC ≈ 0.97). Variable-importance analysis identified NDVI as the dominant predictor, highlighting the role of vegetation condition and fuel availability. Wind-related meteorological variables also showed strong influence, consistent with their role in fire spread and extreme fire behavior. Population density indicated significant anthropogenic contribution to ignition probability and landscape exposure, while topographic parameters provided secondary control. These results demonstrate that wildfire susceptibility in Muğla is governed by a coupled climate–

vegetation–human system. Reserving the 2021 extreme fire season for validation enables future testing of model performance under severe conditions. Several limitations should be acknowledged. The 1 km spatial resolution may introduce uncertainty in representing fine-scale topographic and vegetation variability in heterogeneous Mediterranean landscapes. In addition, the current framework represents a preliminary methodological demonstration rather than an operational forecasting system. Future work will focus on spatial–temporal validation, higher-resolution analysis, and improved extreme-event generalization. The current implementation should be interpreted as a methodological demonstration framework rather than a finalized operational forecasting model.

Variable-importance analysis identified NDVI as the dominant predictor of wildfire susceptibility, followed by wind-related variables and population density. These findings suggest that wildfire occurrence in Muğla is strongly controlled by the interaction of vegetation dynamics, climatic conditions, and anthropogenic pressure. While topographic variables demonstrated comparatively lower importance, they still contributed meaningfully to the spatial susceptibility patterns observed across the study area. Overall, the results highlight the multidimensional nature of wildfire susceptibility in Mediterranean landscapes and support the integration of environmental and human-related predictors in susceptibility modeling.

Variable-importance analysis identified NDVI as the dominant predictor of wildfire susceptibility, followed by wind-related variables and population density. These findings suggest that wildfire occurrence in Muğla is strongly influenced by coupled vegetation, climatic, and anthropogenic controls. Topographic variables demonstrated comparatively lower but still meaningful contributions to the observed susceptibility patterns. The variable-importance ranking is presented in Figure 1.



**Figure 1.** Random Forest variable-importance ranking of environmental predictors influencing wildfire susceptibility in Muğla Province.

## 5. Conclusions

This study presents an interpretable machine learning framework for wildfire susceptibility analysis in a Mediterranean landscape. Integration of multi-source geospatial data and interpretable Random Forest modeling enables identification of dominant environmental drivers while maintaining methodological transparency. The framework

provides a transferable basis for extreme wildfire susceptibility assessment and supports the development of evidence-based wildfire risk management strategies.

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**Conflicts of Interest:** The authors declare no conflict of interest.

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