Forest Fire Prediction Models in Portugal: A Comprehensive Review

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Abstract—**Amid increasing forest fire threats in Europe, particularly the Mediterranean, Portugal stands out due to its disproportionately high wildfire incidents. The 2017 wildfire season alone consumed 6% of the Portuguese territory, highlighting an urgent call for effective solutions. While the National Lookout Towers Network (NLTN) is pivotal in fire prediction in Portugal, it covers only 31% of the mainland with single tower arrangements, leaving significant areas, including 17% designated as high-priority, vulnerable. This paper reviews various forest fire prediction models tailored for Portugal, including machine learning and other methodologies. The inherent challenges in these models include skewed data distribution, feature selection optimization, and overfitting. Prospective enhancements suggest integrating diverse data and ensuring adaptability to Mediterranean regions. The forest fire simulation modeling approach presented in this study holds significant potential for broader applications in the context of forest fire management in fire-prone regions, thereby offering valuable insights into addressing this pressing issue.**

Keywords—Forest fires prediction model, machine learning, Portugal

I. INTRODUCTION

Forests, those sprawling and verdant expanses dominated by majestic trees and a rich tapestry of vegetation, play an indispensable role in our lives. They provide sustenance, shelter, clothing, and even the air we breathe, serving as an abundant source of life-sustaining oxygen [5]. Despite their vital contributions, these woodlands are fragile in the face of a global threat which is defined as forest fires. Once ignited, forest fires can cause significant harm to the environment, economy, and society. Recent years have witnessed the tragic loss of numerous species, escalating soil erosion, and the stark depletion of lush vegetation, resulting in damaged terrain. The undeniable adverse effects on infrastructure and property resulting from these conflagrations have left communities contending with the aftermath of devastation. The intricate relationship between fire and forests is a crucial part of our planet's carbon cycle, influenced by weather conditions, flammable materials, and human actions [6]. This has far-reaching consequences, from harming the environment and economies to endangering human lives [1]. Human health is at risk due to the smoke, which worsens respiratory and heart problems, causing suffering in its wake [5].

Various studies have explored the evolution and geographical spread of wildfires over time, revealing a troubling pattern [1]. In recent decades, Europe has witnessed a marked increase in wildfires, particularly in the Mediterranean region, where environmental conditions favor their occurrence [11]. Despite its smaller size compared to other Mediterranean nations, Portugal has been severely affected by these wildfires [7]. Mainland Portugal spans 18 districts across 90,000 square kilometers in southwestern continental Europe on the Iberian Peninsula, situated between 37° N and 42° N latitude and 6° W to 10° W longitude. Its landscape is diverse, featuring rugged mountains in the north and flat or gently rolling terrain in the south, as illustrated in Figure 1. Portugal experiences a Mediterranean climate with wet winters and hot, dry summers. The duration of the dry season increases as one moves southward and inland [8].

Unmanned Aerial Vehicles (UAVs) can be used in the detection and monitoring of forest fires, with a particular focus on the diverse landscapes of Portugal. Portugal, characterized by its extensive forested areas, has historically been vulnerable to devastating forest fires, emphasizing the need for innovative and effective fire detection methods. UAVs, equipped with advanced sensors and imaging technologies, offer a promising solution. They provide real-time data and high-resolution imagery, crucial for early fire detection and the assessment of fire behavior. By analyzing case studies from recent forest fires in Portugal, such as the tragic 2017 Pedrógão Grande fire, this paper will demonstrate how UAVs can significantly enhance fire detection capabilities. The integration of UAVs not only aids in rapid response but also in the strategic allocation of firefighting resources, potentially mitigating the impact of such disasters. This study aims to contribute to the growing body of research on UAV applications in environmental monitoring, specifically in the context of forest fire management and prevention [19].

While some other Southern European countries are taking different approaches, Portugal has been grappling with a consistent increase in forest fires and the resultant expansion of burned land. Despite increased investments in fire prevention and suppression, approximately 25% of Portugal's land was scorched between 1990 and 2005. The years 2003 and 2005 witnessed particularly devastating fires, affecting an estimated 750,000 hectares [1]. Moreover, in the 2017 wildfire season in Portugal, an unprecedented 6% of the country's land was devoured by flames, underscoring the pressing need for a long-term solution. This dire situation was exacerbated by extreme fire weather conditions, characterized by high Fire Weather Index (FWI) values, wind speeds exceeding 25 km/h, and critically low 1-hour fuel moisture content. These conditions resulted in rapid fire spread rates, including peaks of 4,000 hectares per hour during the Pedrógão Grande fire. What makes matters more challenging is that many of these large fires occurred in close proximity to rural communities with aging populations, limiting their capacity to respond to such severe wildfires [4]. This places Portugal among the most fire-prone countries in Southern Europe. Therefore, this paper aims to provide an overview of the current state of fire prediction in Portugal and to present the developed fire prediction models specific to Portugal which are available in the literature. Data has been gathered from published research studies previously to prepare a comprehensive analysis of the forest fire prediction status of Portugal at present and to suggest improvements for forest fire prediction and mitigation in Portugal which has been identified as one of the victimized countries from forest fires globally.

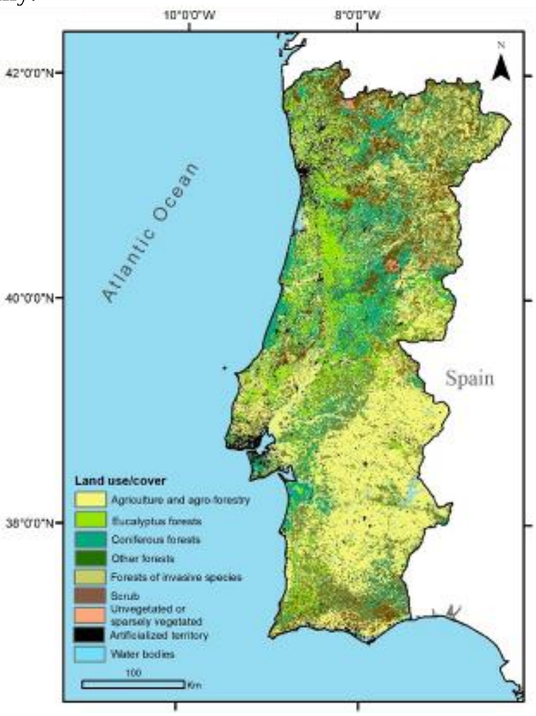

Fig. 1 : Variation of altitude in Mainland Portugal (Source : [3])

II. Forest Fire Prediction in Portugal

In recent years, the importance of forest fire prediction, prevention, and management strategies has significantly increased [10]. The development of systems for forecasting forest fire risks has become a crucial tool for assessing the likelihood of forest fires. Furthermore, predicting the geographical areas where fires are likely to start proves invaluable for forest managers, enhancing the efficiency of resource allocation for fire prevention, detection, and firefighting efforts [11]. These systems not only assist in evaluating the risk of forest fires but also play a pivotal role in supporting ongoing monitoring and suppression efforts during fire outbreaks. Additionally, they contribute to the strategic planning of fire control measures and the efficient allocation of resources for fire management. Portugal distinguishes itself among Southern European countries due to its alarming frequency of wildfire ignitions, underscoring the need for a concerted effort to predict the spatial distribution of these ignitions. This predictive capability holds immense significance for effective fire management, as it enhances the allocation of resources for prevention, detection, and firefighting, a perspective shared by experts [11]. The urgency in developing this forecasting tool arises from the multifaceted impact of forest fires, which cause economic and ecological damage while endangering human lives. Timely detection emerges as a pivotal factor in mitigating these consequences, necessitating agile and efficient fire management strategies [7].

The Ministry of Agriculture and Rural Development in Portugal (Ministério da Agricultura e do Desenvolvimento Rural) is instrumental in the management of forest fires by establishing policies and regulations, promoting fire prevention and safe forest management, providing resources for firefighting, and collaborating with various stakeholders to reduce fire risk and enhance the country's ability to respond to forest fire emergencies. Further, In Portugal, fire prediction and management are critical areas overseen by several institutions e.i. Institute for the Conservation of Nature and Forests (Instituto da Conservação da Natureza e das Florestas (ICNF)), National Authority for Civil Protection (Autoridade Nacional de Emergência e Proteção Civil (ANEPC)), Portuguese Institute for the Sea and the Atmosphere (Instituto Português do Mar e da Atmosfera (IPMA)), Higher Institute of Agronomy (Instituto Superior de Agronomia (ISA)), Forest Technical Office Gabinete Técnico Florestal (GTF)), Institute of Agrarian Development and Forestry (Instituto de Desenvolvimento Agrário e Florestal - IDAF).

The Institute for the Conservation of Nature and Forests is responsible for the management and conservation of natural resources in Portugal, including forests. They play a vital role in wildfire prevention through forest management and regulations. The National Authority for Civil Protection is responsible for coordinating and managing emergency responses, including wildfires. They play a central role in organizing resources and actions during wildfire events. The Portuguese Institute for the Sea and the Atmosphere is responsible for monitoring weather conditions and providing early warnings for extreme events, including fire weather forecasts. The Higher Institute of Agronomy is a leading academic institution in Portugal with expertise in forestry and environmental sciences. They contribute to research and education in fire prediction and management. The National Command for Emergency Operations is responsible for coordinating responses to various emergencies, including forest fires. The Forest Technical Office operates at the municipal level and works on fire prevention strategies, including land management and local community engagement. The Institute of Agrarian Development and Forestry in Portugal contributes to the prevention and management of forest fires by conducting research, implementing forest management practices, enforcing regulations, and coordinating with other agencies and stakeholders. They play a crucial role in reducing the risk of forest fires and ensuring a prompt and effective response when wildfires do occur. These institutions collaborate to monitor, predict, and manage wildfires in Portugal, aiming to mitigate their impact on the environment and communities.

In Portugal, the primary fire detection system is the National Lookout Towers Network (NLTN). However, its effectiveness and coverage have been subject to limited exploration. Recent assessments have revealed that 28% of mainland Portugal lacks NLTN coverage, while 31% relies on a single lookout tower, which is insufficient for adequate fire detection. Approximately 17% of the territory represents high-priority areas for fire surveillance due to poor lookout visibility and high fire risk. However, despite regional variations, there is a relatively low percentage of initial fire detections made by lookout towers, and this percentage seems to be on a decline [2]. To prevent large-scale wildfires, the effectiveness of preventive measures, vigilance, and rapid response operations is of utmost importance. However, the success of these efforts depends heavily on early detection. Given the costliness and subjectivity of traditional human surveillance, there is a concerted effort to adopt automated solutions. Recognizing the pivotal role of fire detection systems in minimizing losses, it is essential to comprehensively evaluate their operational efficiency to optimize resource allocation [12].

At the heart of Portugal's historical landscape lie wildfires that have shaped the nation's terrain. However, contemporary times have witnessed a surge in large wildfires, causing severe degradation in substantial areas of the country. These extensive blazes, spanning over 100 hectares each, serve as a stark reminder of the pressing need for innovative strategies to address this ecological crisis [9]. As Portugal struggles with the evolving fire scenario, understanding the intricacies of ignition patterns, detection systems, and the changing fire landscape remains imperative for preserving both the environment and the inhabitants it shelters.

III. Reported Fire Prediction Models Developed for Portuga

Numerous fire prediction models have been developed for forecasting fires in Portugal, and these studies have been summarized as follows (Table 1). A significant portion of these models fall into the category of machine learning-based fire prediction models. They encompass both supervised and unsupervised machine learning techniques in their model development. Furthermore, while some models were designed to provide predictions for the entire nation of Portugal, others are specifically tailored to address fire predictions in particular regions of the country.

A. Machine Learning Based Models

Based on the forest fire data, a forest fire prediction model for the Northern region of Portugal was developed using machine learning techniques, including Multiple Regression (MR), Decision Trees (DT), Random Forests (RF), Neural Networks (NN), and Support Vector Machines (SVM). The model incorporated various variables, such as spatial, temporal, Fire Weather Index (FWI) components (an indicator of fire intensity), and weather attributes (temperature, relative humidity, rain, and wind speed). After rigorous evaluation, the SVM model with four direct weather inputs (i.e., temperature, rain, relative humidity, and wind speed) was identified as the best configuration. This model demonstrates proficiency in predicting small fires but exhibits lower accuracy in forecasting large fires. Notably, this represents the first instance where burn area prediction is solely based on meteorological data. Furthermore, parameters like vegetation type and firefighting interventions such as time elapsed and firefighting strategy can be incorporated to enhance the model's accuracy [7].

In parallel, a Support Vector Method (SVM) model was introduced using recent real-world data collected from the northeast of Portugal by [15]. Parallel SVM considers the Forecast Weather Index (FWI) and some weather parameters for the prediction of a forest fire and the parallel SVM model reduces the computational time and high storage required for the analysis. In the Portugal dataset, the parallel SVM model demonstrates a RMSE of 63.45, while the conventional SVM method yields an RMSE of 63.5. Therefore, developed models from conventional methods show a higher accuracy comparatively.

By the way, the study in [1] encompassed various Machine Learning approaches, such as extreme gradient boosting (XGBoost), random forest (RF), support vector machine (SVM), and decision tree (DT). This research was conducted using data from Montesinho Natural Park, with a monthly dataset spanning from January 2000 to December 2003. The data was categorized into two sets, distinguishing between flammable and non-flammable areas using the K-means++ clustering technique. For the variables, including X and Y coordinates, FFMC, DMC, DC, ISI, temperature, relative humidity (RH), wind, and rainfall, the XGBoost model exhibited superior performance, as evidenced by three evaluation metrics (ACC = 0.8132, F1 = 0.7862, and AUC = 0.8052). Furthermore, it's worth noting that the ACC, F1, and AUC values are higher in machine learning models based on spatiotemporal characteristics rather than models classifying wildfires by their burned area size, indicating that spatiotemporal heterogeneity has a significant impact on wildfire occurrence. Even though this [1] reveals that XGBoost model performed well than SVM, RF, DT the duration of dataset is limited in here compared to the study [7] and [15].

On the other hand, regression models also performed well according to the following studies. In a separate study, reference [11] developed a model utilizing the logistic regression method, encompassing the entire mainland of Portugal. This model utilized forest fire data from the period 2001-2005, sourced from the Portuguese Forest Services. The variables considered in this model included population density, human accessibility, land cover, and elevation. Analysis of the receiver operating characteristic curve (ROC) curve reveals that 87.2% concordance between predicted probabilities and observed outcomes while with the confusion matrix method achieved a global accuracy of 80.3%. This model underscores that human presence and activity serve as the primary drivers of fire ignitions in Portugal, with population density emerging as the most significant contributing factor. Notably, the majority of ignitions (85%) were concentrated in areas characterized by a blend of agriculture and urban-rural elements, whereas only 15% occurred in forested or uncultivated areas, despite the latter covering half of the country's land area. Agriculture stands out as a prominent factor influencing the initiation of fires, while forests, shrublands, and sparsely vegetated areas also exhibited a positive influence on ignition occurrence, though their impact was comparatively lower.

Another machine learning model, based on Extreme Learning Machines (ELM), was implemented and compared with Linear Regression, Random Forest Regression, and Support Vector Regression (SVR) methods. The dataset for this study was sourced from Montenshino Natural Park in Portugal and comprised a total of 517 forest fire incidents. This dataset encompassed 13 attributes and 517 data entries, with features including variables such as X, Y, month, day, FFMC (fine fuel moisture code), DMC (duff moisture code), DC (drought code), ISI (initial spread index), temperature, relative humidity (RH), wind, and rainfall. In this study, the ELM method produced an RMSE (Root Mean Square Error) value of 63.09511. The results of this comparison indicate that the ELM method can yield outcomes that are competitive with the Linear Regression method. Furthermore, it can be inferred that, when working with this dataset, the most effective methods for addressing forest fire prediction cases are Linear Regression and ELM [13]. Fire prediction using linear regression, ridge regression, and lasso regression was done in [14]. It is based on Montesinos park and climate, and physical factors were considered as variables. The accuracy of the linear regression algorithm gives higher accuracy than ridge regression and lasso regression algorithms.

Three regression models were developed in reference [3] and each model is developed using different independent variables: one using only susceptibility (Susc), another using only the absolute values of Seasonal Severity Rating (SSRAbs), and the third using both Susc and SSRAbs. These models were applied to analyze the annual burnt areas of Mainland Portugal over a 24-year period, from 1995 to 2018. The data was sourced in vector format from the Portuguese Institute for Nature Conservation and Forests (ICNF), with key parameters including slope, elevation, and land cover. When combining the index with wildfire susceptibility, there was a slight increase in the model's capability to predict areas that would burn, compared to using susceptibility alone. The spring meteorological context was found to be more suitable for predicting the severity of the upcoming summer wildfire season, rather than pinpointing the specific locations of wildfires. The highest Likelihood Ratio was observed in the elevation class of 1000m-1500m (LR-3.2786), with slope angles less than 20º (LR-2.5817), and in areas with sparse vegetation (LR-3.6347). The authors also proposed that the model could be updated annually following the critical wildfire season and applied to optimize the allocation of human and material resources for prevention, early detection, and suppression activities, all aimed at reducing the severity of wildfires in the country.

Conversely, a Sparse Autoencoder-based deep neural network, coupled with an innovative data balancing procedure involving Artificial Neural Networks (ANN), Support Vector Machines (SVM), and Random Forest (RF), was implemented using forest fire data collected between 2000 and 2003 from Portugal's Montesinho Natural Park, comprising a total of 517 records [16]. This proposed method exhibits superior accuracy in predicting large-scale forest fires. This approach holds the potential to significantly enhance wildland fire management and preclude serious fire accidents. However, constructing prediction models can be challenging due to the need for selecting the most relevant features for the prediction task and handling the substantial imbalance in data distribution, where the number of large-scale forest fires is notably lower than that of small-scale incidents.

Moreover, a combination of remote sensing techniques and machine learning (specifically, Random Forest) supported forest fire prediction. The study utilized Landsat surface reflectance (SR) data for Northwest Portugal, featuring a resolution of 30 meters (level 2, collection 2, tier 1) spanning from 2001 to 2020 [9]. The results revealed that, based on the derived burnt area maps, approximately 23.5% of the territory experienced at least one fire event between 2001 and 2020. The temporal analysis of burnt areas indicated an average impact of 6,504 hectares within the 20-year timeframe. Annual burnt area figures exhibited variability, with the lowest recorded in 2014 (679.5 hectares) and the highest mapped area observed in 2005 (73,025.1 hectares). Therefore, SVM and Regression models outperform than the other models while most of them are suitable for large-scale fires only. Also, anthropogenic factors have a higher impact on forest fires similar as the weather inputs.

B. Other Models

An evaluation of the National Lookout Towers Network (NLTN) using Geographic Information Systems (GIS) was conducted in a study by [2]. This evaluation encompassed the entire mainland of Portugal. The results of this assessment indicate that the National Lookout Towers Network plays a crucial role in fire detection in specific regions of Portugal. However, in other regions, its effectiveness in detecting wildfires is notably limited, accounting for only a small percentage of total wildfires.

Also, NLNT is more efficient during the day than other detection systems, but less efficient at night. At least about 34% of the Portuguese mainland has a very low or low probability of a fire being detected by lookouts, and 17% of the territory has high priority in terms of complementary fire vigilance, due to its high fire risk and low NLNT vigilance. The areas where additional fire vigilance is more necessary, complementarily to the NLTN system were identified. Relation between the estimated visibility or detection probability and the percentage of wildfires effectively detected by the NLNT system between 2001 and 2003 and verified very good adjustments (R^2 = 0.97 to R^2 = 0.88).

In reference [8], which focused on the Portuguese mainland and examined records spanning from 1996 to 2015, drawn from the Portuguese Institute for Nature and Forests Conservation (ICNF) database, relevant validated statistics reveal that out of the total recorded fire events, 94.4% were confirmed as actual occurrences. Among these, 22.2% had burned an area exceeding 1 hectare, and of these, only 42.1% were thoroughly investigated. Notably, false alarms or fires without a recorded burning area were more prevalent in the districts of Aveiro, Lisbon, and Porto, which are the largest municipalities. When examining the causes of investigated fires, it was observed that the majority of recorded events occurred in the northeastern regions (49.0%), followed by the northwestern regions (41.7%), with the rest of the country accounting for 9.3%. A more in-depth analysis, considering the ratio between investigated fires and the total number of fires, provided a different perspective, with the central and southern regions showing more diligence in investigating fires. A comprehensive analysis of the causes and motivations behind the ignition of these forest fire incidents revealed that human activity, whether deliberate (20.4%) or negligent (29.9%), surpassed natural phenomena (0.6%). Over time, reactivations (14.6%) and unknown (34.5%) causes decreased, while negligent and deliberate causes increased.

Minimum Travel Time algorithm was employed in [4], incorporating variables such as wildfire season winds (speed and direction), frequency scenarios, and fuel moisture content. The study revealed that 10,394 structures were exposed to fire each year, with 30% of communities accounting for 82% of this total. The predicted burned area in natural sites amounted to 18,257 hectares annually, of which 9.8% was located in protected land where fuel management is not permitted. Notably, the primary burn probability hotspots were identified in the central and northern regions. This study underlines critical priorities for safeguarding the most vulnerable communities and promoting national-level landscape management programs. Moreover, this research is valuable in informing Portugal's new national plan, currently in implementation, which relies on a probabilistic methodology for decision-making. In terms of future directions, the wildfire simulation modeling approach presented in this study can be extended to other fire-prone Mediterranean regions, where predicting catastrophic fires can play a crucial role in anticipating and mitigating future disasters.

Fuel Breakdown Network (FBN) has been developed in [17]. Data on residential buildings were acquired as spatial points from the Instituto Nacional de Estatistica, and input data for the wildfire simulation modeling library were sourced from a previous study. Regarding the planned Fuel Breakdown Network (FBN), the results indicated the potential for reducing the annual burned area from large fires by up to 13% (equivalent to approximately 13,000 hectares), cutting the annual number of exposed residential buildings by up to 8% (around 100 residential buildings), and decreasing the annual burned area in protected areas by up to 14% (approximately 2,400 hectares). The expected burn-over percentage varied considerably across different segments in response to estimated fire intensity, resulting in an average decrease of 40% in overall effectiveness. Notably, the most critical fuel breaks exhibited a higher percentage of fire burn-over and, consequently, a reduced level of effectiveness. Additionally, it was revealed that the current implementation of the FBN follows a random sequence, which is suboptimal for achieving all objectives.

Susceptibility models were developed for mainland Portugal using the Likelihood Ratio method[18]. The input dataset consisted of burned areas over 44 years, along with a set of predisposing factors related to topography and land cover. The results of this study highlight areas where the combination of terrain features is more favorable for fire propagation. Notably, the highest favorability scores were associated with shrubland-type vegetation, while agricultural areas, cork, and holm forests exhibited lower scores. Eucalyptus and maritime pine forests displayed intermediate scores, and their presence has increased since 2007. The two highest hazard classes correctly classified 90% of the burned area over 44 years, underscoring the model's high accuracy. If these hazard classifications are integrated into spatial planning instruments, in conjunction with municipal plans, they can potentially restrain the expansion of built-up areas. It's noteworthy that approximately 2% of municipalities have over 90% of their territory classified as hazardous, whereas 32% of municipalities have less than 10% of their area falling into the hazardous category. These structural maps provide a valuable foundation for a long-term approach and can be supplemented with estimations regarding the behavior and severity of wildfires, which warrants further exploration.

IV. Limitations and Challenges

In the domain of forest fire prediction for Portugal, there are significant challenges and limitations. Existing predictive methods, such as the Cascade Correlation Network (CCN), Radial Basis Function (RBF), and Support Vector Machine (SVM), have demonstrated their limitations in addressing the intricate dynamics of forest fires. They often suffer from overfitting issues and reduced predictive accuracy, particularly when dealing with large fires [7], [15]. While the conventional SVM excels at predicting small fires, it struggles to provide accurate forecasts for large-scale fires [15]. These challenges are further compounded by the inherent difficulty in constructing prediction models. This difficulty stems from the twin challenges of selecting the most relevant features for prediction [16] and contending with a data distribution that is heavily skewed toward small-scale fires. This skewed distribution results in a disproportionate scarcity of information on large-scale forest fires [16].

V. Recommendations and Future Directions

Looking forward, the forest fire prediction models in Portugal have room for refinement and expansion. Beyond the scope of this study, the incorporation of critical details such as vegetation types and specific firefighting interventions, including factors like elapsed time and employed strategies, holds the potential to enhance predictive accuracy [7]. To drive continuous improvement, an effective strategy involves regular model updates following the critical wildfire season. By aligning resource allocation with insights into prevention, early detection, and suppression strategies, the severity of wildfires could be mitigated [3]. As we move into the future, the wildfire simulation modeling approach introduced here offers promise for broader applications. Its adaptability to other fire-prone Mediterranean regions presents the opportunity for early disaster anticipation and effective management [4]. The exploration of a maximum entropy model customized to Portugal's specific context represents an open pathway, providing opportunities to improve forest fire management and disaster preparedness [18].

VI. Conclusion

Within the European context, Portugal, despite its smaller geographical stature, has encountered a pronounced escalation in wildfire incidents, resulting in substantial areas of charred land. This trend underscores the critical importance of forest fire prediction, prevention, and comprehensive management strategies. A precise prediction of fire ignition locations is fundamental for the judicious deployment of resources and heightened firefighting efficacy. While Portugal's National Lookout Towers Network serves as the primary means for fire detection, it exhibits certain constraints. As timely detection becomes increasingly imperative to prevent expansive wildfires, there's an emerging emphasis on integrating automated tools alongside human-operated systems. A series of advanced machine learning-driven fire prediction models have been introduced. These models, which factor in meteorological conditions, fuel moisture levels, and historical patterns, aim to predict forest fire susceptibilities and refine preventive measures.

Efforts to enhance forest fire prediction models in Portugal face challenges such as overfitting and a tendency to focus on minor fires. Addressing these requires a comprehensive approach that includes varied vegetation types and updated firefighting methods. Regular model updates following major fires are crucial for better resource distribution. The progress made in Portugal's fire prediction models is not only vital for the country, given its high incidence of wildfires, but also offers a framework that could be adapted in other fire-prone areas. Improving these models is key to reducing the ecological and community impact of forest fires, particularly in Southern European regions.

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TABLE 1. SUMMARY OF FIRE PREDICTION MODELS FOR PORTUGAL

Model/Method Used	Data Source	Variables/Features	Model Performance	Key Findings	Limitations & Challenges	Recommendations & Future Directions	Reference
MR, DT, RF, NN, SVM	Northeast region of Portugal.	Spatial, temporal, FWI components, weather attributes	SVM with weather inputs best for small fires.	Meteorological data used for predicting burn area.	Lower accuracy for large fires.	Consider additional information like vegetation type and firefighting intervention for large fires.	[7]
Logistic Regression	Entire Portuguese mainland	Population density, human accessibility, land cover, elevation	Good predictive ability with ROC concordance of 87.2%.	Human presence/activity key drivers of ignitions.	Limited to a specific time period.	Incorporate more recent data and explore other factors influencing ignitions.	[11]
ELM, Linear Regression, RF, SVR	Montenshino Natural Park, Portugal	X, Y, month, day, FFMC, DMC, DC, ISI, temp, RH, wind, rain	ELM with 20 hidden neurons and Linear Regression best.	ELM competitive with Linear Regression.	Data imbalance for small and large-scale fires.	Address data imbalance and optimize for large-scale fire prediction.	[13]
Linear Regression, Ridge, Lasso	Montesinos park, Portugal	Climate and physical factors	Linear Regression showed higher accuracy.	Linear Regression outperformed Ridge and Lasso.	Limited to specific location.	Test on diverse geographic regions and consider more factors.	[14]
Regression models	Mainland Portugal, 1995-2018	Slope, elevation, land cover	Combination of Susc and SSRAbs improved prediction.	Spring meteorological context important.	Update model yearly post-critical wildfire season.	Integrate into spatial planning instruments.	[3]
Parallel SVM	Northeast Portugal	FWI, weather parameters	Parallel SVM reduced computational time.	Reduced computational burden.	Slight reduction in RMSE.	Further optimize computational efficiency.	[15]
XGBoost, RF, SVM, DT	Montesinho Natural Park, 2000-2003	X, Y, FFMC, DMC, DC, ISI, temp, RH, wind, rain	XGBoost performed best with spatiotemporal characteristics.	Spatiotemporal models outperformed area-based models.	Limited to a specific time period.	Consider temporal dynamics for larger prediction windows.	[1]
Sparse autoencoder-based DNN	Montesinho Natural Park, 2000-2003	Various meteorological variables	Improved prediction of large-scale forest fires.	Reduced prediction errors.	Data imbalance for small-scale fires.	Explore feature selection techniques and address data imbalance.	[16]
Random Forest with time series	Northwest Portugal, 2001-2020	Landsat surface reflectance data	23.5% territory burnt; annual burnt area varies.	Temporal variability in burnt area.	Focus on specific region.	Expand analysis to other regions and explore long-term trends.	[9]
Evaluation of National Lookout Towers Network (NLTN) using GIS	Entire Portuguese mainland	Lookout towers' efficiency	NLTN efficient in some regions, less at night.	34% of mainland not well covered by NLTN.	Inefficient at night.	Improve NLTN coverage and nighttime detection.	[2]
Cluster Analysis	Portuguese mainland, 1996-2015	Causes and motivations of forest fires	Human activity major cause.	Regional differences in fire investigations.	Limited to specific time frame.	Analyze trends over time and across regions.	[8]
Minimum Travel Time Algorithm	National wildfire season data	Wildfire winds, frequency scenarios, fuel moisture content	Priorities for safeguarding communities.	Predicted burned area and community exposure.	Specific to wildfire seasons.	Incorporate real-time data for proactive measures.	[4]
Fuel Breakdown Network (FBN)	Mainland Portugal	Residential buildings data, wildfire simulation	Potential reduction in annual burned area and residential buildings exposed.	Effectiveness of fuel breaks varies.	Suboptimal implementation sequence.	Optimize fuel break strategies and implementation.	[17]
Susceptibility models using Likelihood Ratio method	Mainland Portugal	Burned area data, topography, land cover	High accuracy in hazard classification.	Favorability scores for different vegetation types.	Long-term approach needed.	Integrate into spatial planning instruments.	[18]