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WILDFIRE RISK ANALYSIS USING FLAMMAP IN SEMI-ARID MEDITERRANEAN FORESTS

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Abstract

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This study presents a comprehensive approach to assessing wildfire behavior in a Mediterranean landscape using the FlamMap fire moelling software. We employed geospatial tools to map and categorize land cover types, followed by field visits to validate the remote data and collect detailed vegetation and fuel load information. Key physical parameters, including slope, elevation, and historical weather data, were integrated into the FlamMap model to simulate wildfire behavior under two wind scenarios: one with an average wind speed of 10 km/h and another with a maximum wind speed of 23 km/h. The simulations provided detailed insights into fire behavior parameters such as fireline intensity, flame length, and rate of spread (ROS), emphasizing the critical roles of wind speed, vegetation type, and topography. Results showed significant variations in fire behavior across different vegetation types, with the highest fireline intensities and rates of spread occurring in areas dominated by Aleppo pine and dense shrublands, particularly under high wind conditions. The overlay of historical fire data with simulation results revealed that regions with dense shrub stands and Aleppo pine wooded shrub are most prone to wildfires, underscoring the need for targeted fire management strategies. This study demonstrates the utility of FlamMap in predicting fire behavior and guiding wildfire management efforts in high-risk areas.

Key words: wildfire, behavour, moelling, FlamMap, risk.

Introduction

Forests cover approximately 31% of the Earth's land area, playing a crucial role in maintaining global biodiversity, carbon sequestration, and climate regulation (Brunner, Godbold, 2007; Ahirwar, 2023). These ecosystems, however, are increasingly threatened by wildfires, which have become more frequent and severe due to climate change, land-use practices, and other anthropogenic factors (Chen et al., 2024). Wildfires not only cause immediate destruction of vegetation and wildlife habitats but also have long-term ecological impacts, including soil degradation, alteration of water cycles, and loss of species diversity (Cao, 2023; Lopez et al., 2024). The frequency and intensity of these fires disrupt ecosystem processes and can lead to significant economic and social consequences (Kalogiannidis et al., 2023).

The Mediterranean region, characterized by its hot, dry summers and vegetation that is prone to ignition, is one of the most wildfire-prone areas in the world (Moreno et al., 2023). These conditions make the region highly susceptible to frequent and intense wildfires, which have devastating effects on its diverse ecosystems. In Algeria, which is part of the Mediterranean basin, wildfires are a significant concern, particularly in the summer months when high temperatures and dry winds increase fire risk (Ghefar et al., 2024). The country's forests, particularly those dominated by Aleppo pine and cork oak, are particularly vulnerable to these fires (Benzina et al., 2024). The increasing frequency and intensity of wildfires in Algeria have underscored the critical need for effective fire prevention and management strategies.

Understanding and mitigating wildfires necessitates comprehensive and accurate data on fuel loads, topography, and meteorological factors (Nguyen et al., 2024). Fuel characteristics, which encompass the type, quantity, and arrangement of vegetation, are among the most critical factors influencing fire behavior (Calvo et al., 2023). Studies have shown that variations in fuel types can significantly alter fire intensity and spread (Scott, Burgan, 2005; Taneja et al., 2023). Topographical features such as slope and aspect further complicate fire dynamis, as they affect the rate of spread and fireline intensity (Rodrigues et al., 2023). Additionally, meteorological conditions, particularly wind speed and direction, play a pivotal role in determining how a fire evolves (Burton et al., 2023).

To account for these complexities, spatial tools have become indispensable in the analysis and management of wildfires due to their ability to handle and process large, complex datasets that describe environmental conditions across vast landscapes (Zagalikis, 2023). These tools enable the collection, integration, and analysis of spatial data related to key factors like vegetation, topography, and climate, all of which are critical for understanding fire behavior and assessing the associated risks (Santos et al., 2022). By providing a visual and quantitative framework, Geographic Information Systems (GIS) and firrebehavior software allow researchers and land managers to simulate fire dynamics and predict potential outcomes. This integration of spatial data with fire behavior modeling improves the precision of wildfire risk assessments and informs decisio -making on preventive measures and resource allocation.

One of the most widely used fire behavior systems is FlamMap, a software designed to simulate the potential spread and intensity of wildfires over a given landscape (Finney, 2006; Ghodrat et al., 2022). FlamMap leverages a range of inputs, such as fuel type, topography, and weather conditions, to create detailed models of fire behavior. The software calculates outputs like the rate of spread, flame length, fireline intensity, and crown fire potential, which are vital metrics for understanding how a fire might develop in specific environmental conditions (Finney et al., 2023).

Over the past two decades, extensive research has successfully integrated fire behavior simulation models into wildfire risk assessment frameworks, providing critical insights into fire dynamics in various fire-prone regions around the Mediterranean region such as (Alcasena et al., 2017; Yavuz et al., 2018; Palaiologou et al., 2020). However, in Algeria mainly in the study region despite the prevalence of wildfires, many studies have focused primarily on analyzing fire occurrences and impacts rather than utilizing advanced modeling tools to predict fire behavior, where wildfires pose a significant threat to biodiversity and local communities. For instance, researhs works conducted by Bouiadjra et al. (2011), El Zerey (2014), Ghefar and Bouazzaoui (2021), El Bouhissi et al. (2020), and Ghefar et al. (2024) haas examined wildfire patterns, fire causes, and ecological consequences, but their approaches did not incorporate the use of fire behavior models for predictive purposes. This gap highlights the need for further development and application of fire simulation models in the Mediterranean context to enhance the accuracy of wildfire risk assessments and improve fire management strategies in the region.

In this study, we utilize GIS and fire behavior modeling to analyze the wildfire risk in a Mediterranean landscape in Algeria. The study area, characterized by its complex topography and diverse vegetation, presents a challenging environment for fire management. By integrating geospatial data with fire modeling tools like FlamMap, we aim to simulate potential fire behavior under various environmental conditions, assess the impact of different factors on fire dynamics, and identify areas that require targeted management interventions. The insights gained from this research are intended to inform fire prevention and mitigation strategies, contributing to the protection of Algeria's valuable forest ecosystems.

Material and methods

Study area

The Zegla Forest, located in the southern part of Sidi Bel Abbes province in Algeria, occupies the southern slopes of the Dhaya Mountains, located between the Saida Mountains to the east and the Tlemcen Mountains to the west, and spans an area of 47,238 ha. This semi-arid territry, is characterized by a bioclimate with annual rainfall ranging from 320 to 380 mm, with the highest precipitation during spring and winter (Benabdeli, 1996). The forest's soil types, including rendzinas, calcareous brown soils, and shallow terra rossa, consist of two horizons that restrict water infiltration and root depth, significantly influencing local flora and vegetation distribution (Benabdeli, 1996). The pedoclimatic conditions of thst forest create a fragile Mediterranean ecosystem, which is prone to frequent environmental disturbances such as wildfires. This territory, with its specific management challenges, demands strategies that address its susceptibility to fire and ecological fragility while maintaining its biodiversity and supporting sustainable resource use.

Data

To assess wildfire behavior using FlamMap, a systematic and detailed approach is essential, ensuring accurate inputs for the simulation process. The first step involves gathering detailed fuel data, as fuel characteristics significantly influence fire behavior under various environmental conditions. We began by employing geospatial tools such as Google Earth to obtain a comprehensive overview of the forested areas and the surrounding landscape within the study region. Satellite imagery from Google Earth was combined with available geospatial data to map and analyze landscape features, including forested areas, agricultural lands, and other land-use types.

Using QGIS, we performed the land cover, categorizing the landscape into distinct land cover types based on their characteristics. This classification process involved assigning visual distinctions to each land category, allowing for clear visualization of the spatial distribution of different fuels across the study area. The geospatial analysis was further enhanced by field visits, which were critical for validating the remote sensing data. During these field visits, we conducted on-site comparisons to verify the accuracy of the geospatial data, gathered additional environmental information, and characterized the vegetation in the area.

Vegetation types were classified based on visual observations, where we identified dominant plant species and collected dendrometric data to understand the structural characteristics of the forest. To evaluate forest fuel loads, we established 20 representative sampling points per land cover category. At each sampling point, systematic measurements of key fuel parameters were taken, including canopy cover, stand height, crown base height, and canopy bulk density, following established methodologies (Scott, Reinhardt, 2001; Taneja et al., 2023; Bitella et al., 2024). These data were meticulously compiled into a detailed database, which forms the foundation for accurately modeling wildfire behavior using FlamMap. This database allows us to input precise environmental variables into the fire modeling system, ensuring that the simulations reflect the true fire potential and risk within the study region.

Once the fuel types have been identified, they are then translated into specific fuel models that can be used in FlamMap. These models are selected from standard fuel models (Scott, Burgan, 2005), and they are widely custom-built to reflect the unique conditions of the study area more accurately. This step ensures that the fuel inputs into FlamMap are as realistic and

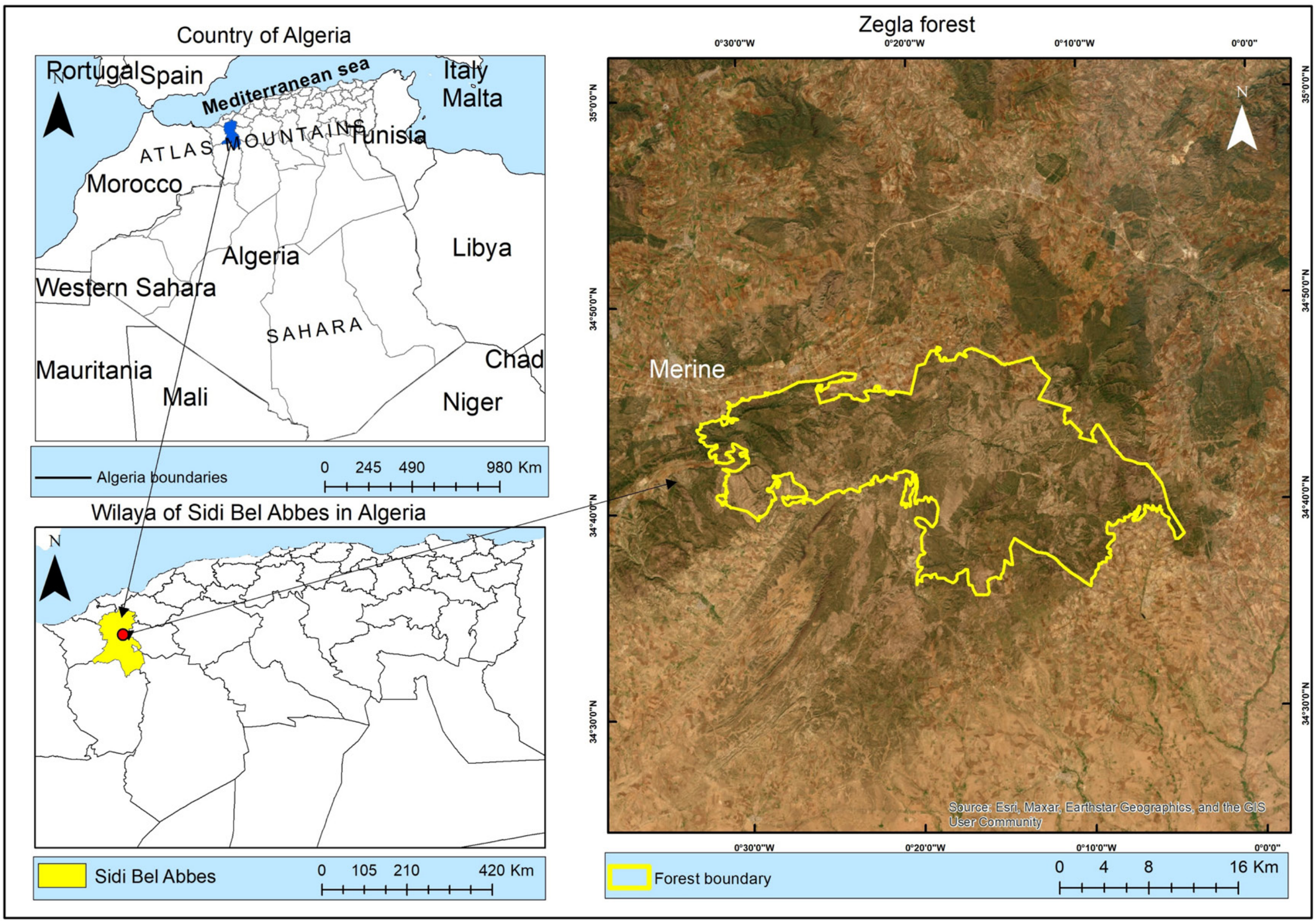

Fig. 1. Location of the study area.

representative as possible, allowing for more accurate simulations of fire behavior under the different temperature scenarios being studied.

The second step involves the collection of physical data such as slope aspect, elevation, and historical weather data, which forms the backbone of the simulation procesis These data incldes critical parameters such as daily maximum and average temperatures, wind speed, and wind direction. To ensure accuracy, and in the lack of local weather stations, we utilized hourly records from Nasa power data website (Nasa, 2024). The chosen period for this data collection typically corresponds to the peak fire season in the study area.

The QGIS software was utilized for managing spatial data and generating all the necessary input layers required for executing FlamMap simulations. All spatial data used to define the Landscape file were processed with a grid resolution of 30 meters to ensure accurate representation. Elevation, slope, and aspect maps were derived from digital elevation model (DEM), providing essential topographical information for the study area. To accurately depict fuel and canopy characteristics, we combined data from field investigations with a detailed land cover map of the region, resulting in comprehensive maps that classified the primary vegetation types and land uses. The study area was meticulously divided into ten distinct land cover types, each associated with either a standard or custom fuel model tailored to the specific conditions observed in the field. These classifications were then integrated to create a landscape (LCP) file, which served as the foundational input for FlamMap simulations, ensuring that the model accurately reflected the diverse and complex fuel conditions present across the study area.

Fire modelling

Wildfire exposure modeling utilized the Minimum Travel Time (MTT) fire growth algorithm, a globally recognized method for simulating fire spread across various scales. The MTT algorihm, based on Huygens' principle and Rothermel's surface fire spread moel, predicts fire expansion by treating the fire edge as a vector or wavefront. The simulation was set for a 2-hour duration, reflecting typical active spread periods in major wildfire events in the study area. To enhance the accuracy of ignition modeling, artificial neural networks (ANNs) were used to create a high-resolution ignition probability grid with a 10-meter spatial resoluton, based on historical fire data from 2000 to 2023, encompassing 150 fire incidents. This grid informed the generation of an input file with 10,000 ignition points, specifically selected and masked for areas with combustible fuels, ensuring precise simulation of fire behavior in the landscape.

Table 1. Fuel moels parameters and land cover types.

Fm Type	Load of dead fuel particles up to 6 mm (kg/m²)	Load of dead fuel particles 6–25 mm (kg/m²)	Load of dead fuel particles 25–75 mm (kg/m²)	Load of live herbaceous fuel (kg/m²)	Load of fine live woody fuel (kg/m²)
Agriculture	0.01	0.01	0.01	0.01	0.00
Grass	0.22	4.93	0.00	0.67	0.00
Aleppo pine and cork holm forest	0.45	2.02	3.36	0.45	0.90
Aleppo pine forest	0.50	2.20	2.80	0.45	0.90
Aleppo pine wooded shrub	7.85	11.88	4.93	0.90	7.62
Aleppo pine and cork holm wooded shrub	8.20	10.05	5.00	0.90	7.62
Aleppo pine and eucalyptus forest	10.09	3.20	5.40	0.80	4.48
Aleppo pine and thouja wooded shrub	7.85	11.88	4.93	0.90	7.62
Degraded shrub	0.25	0.25	0.00	0.15	1.30
Dense shrub	7.85	11.88	4.93	0.90	7.62
Aleppo pine regeneration	0.22	4.93	0.00	0.67	0.20

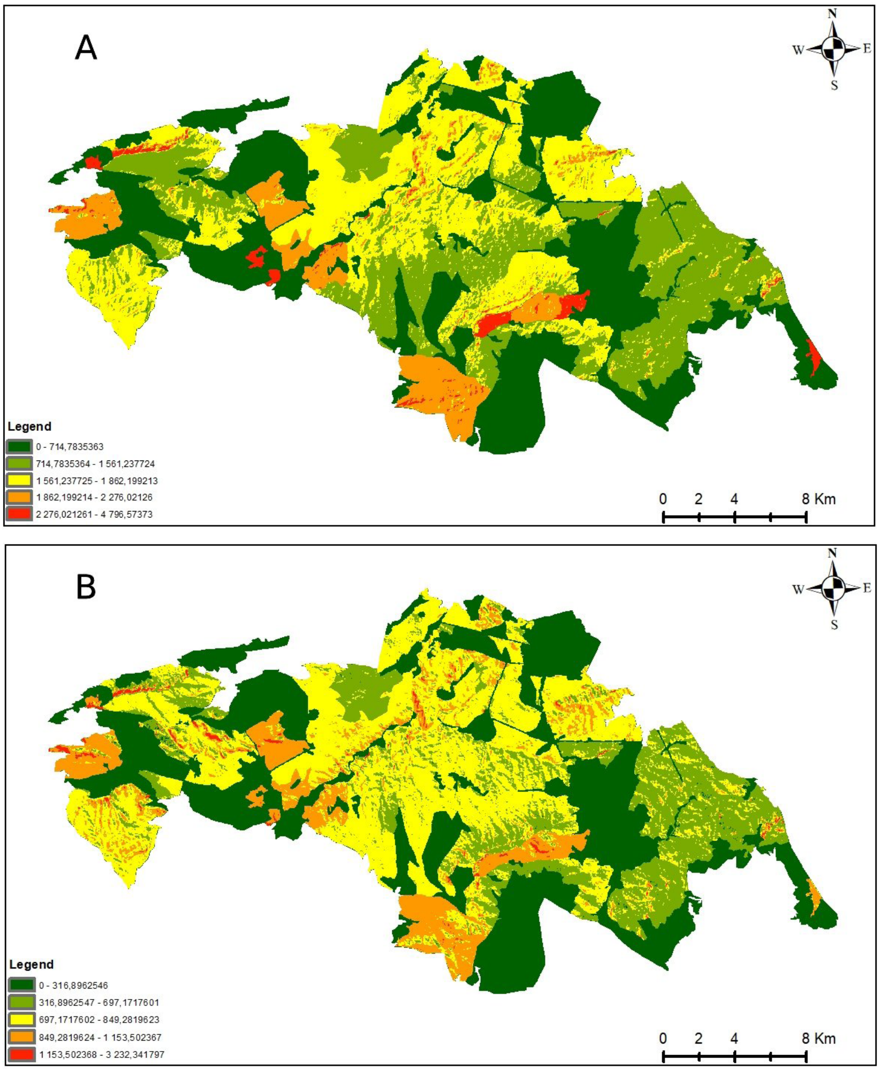

Fig. 2. Fireline intensity under varying wind speed conditions (A: 23 km/h; B: 10 km/h).

Two scenarios were developed to evaluate wildfire behavior under varying wind conditions. The first scenario applied the maximum recorded wind speed of 23 km/h, while the second scenario used the average wind speed of 10 km/h for the study period. For wind direction, the maximum wind scenario incorporated the average direction recorded on days with peak wind speeds, ensuring alignment with the higher wind intensity. Conversely, the average wind scenario employed the average wind direction calculated over the period to represent typical wind conditions. Fuel moisture content data were sourced from field investigations and existing literature (Pellizzaro et al., 2007; Salis et al., 2009; González-Olabarria et al., 2012; Salis et al., 2015).

FlamMap simulations were conducted for both scenarios, generating outputs including rate of spread, flame length, fireline intensity, burn probability, and crown fire activity, thus providing a comprehensive assessment of how different wind speeds and directions influence wildfire dynamics.

Results

The landscape is predominantly characterized by Aleppo pine and cork holm wooded shrub, which dominates with 30.94% of the total area, translating to 15,266 ha. This extensive coverage highlights the significant role of this vegetation type in the region. Following closely is dense shrubland, covering 24.45% of the area, or 12,064 ha, indicating a substantial presence of robust, thick shrub growth suchas, cork holm, lentiscus, and calycotome. Agricultural land occupies 10.52% of the area, amounting to 5,190.70 ha, reflecting a significant human influence on the landscape. Degraded shrubland covers 12.81% of the total area, or 6,319.56 ha, suggesting areas that have experienced deterioration mainly by wildfire. Aleppo pine and cork holm forest contributes 7.12% to the landscape, equating to 3514.33 ha, while Aleppo pine wooded shrubland represents 4.45% of the area, covering 2 193.23 ha. Additionally, Aleppo pine and thuja wooded shrubland constitutes 5.54% (2731.81 ha), indicating a diverse mix of shrubs. Aleppo pine regeneration, an area of 989.14 ha, accounts for 2.00% of the landscape, pointing to ongoing efforts in vegetation recovery. Smaller areas include Aleppo pine forest at 1.11% (547.21 ha) and Aleppo pine and eucalyptus forest at 0.34% (168.78 ha). Grassland and other minor vegetation types make up a minimal part of the total area, with grassland alone at 0.72%, covering 352.81 ha. This detailed breakdown underscores the varied and complex nature of the landscape, dominated by significant shrub and forest types, with more minor contributions from grasslands and other vegetation (Table 1).

Fireline intensity

In this study, we have analyzed fire behavior using the FlamMap software under natural conditions across two scenarios: one with an average wind speed of 10 km/h and another with a maximum wind speed of 23 km/h. The analysis focused on fireline intensity across various vegetation and forest management types. The results showed that at the lower wind speed of 10 km/h, fireline intensity varied considerably depending on the type of vegetation. In degraded shrub and grass areas, the fireline intensity was relatively low, measuring 316 kW/m. This lower intensity can be attributed to the sparse and less flammable nature of the fuel load in these areas. By contrast, areas dominated by more substantial and continuous vegetation, such as the mixed Aleppo pine, cork holm, and thouja wooded shrub areas, exhibited much higher fireline intensities, reaching up to 3,232 kW/m. This increase reflects the higher availability of fuel, which supports more intense and sustained burning under moderate wind conditions.

When the wind speed increased to 23 km/h, the fireline intensities across all vegetation types escalated significantly. The degraded shrub and grass areas, which had the lowest fireline intensity at 10 km/h, saw an increase to 714 kW/m. This doubling in intensity demonstrates the critical role that wind plays in enhancing fire spread, even in areas with lighter fuels. The most pronounced increase was observed in the mixed Aleppo pine, cork holm, and thouja wooded shrub areas, where fireline intensity surged to 4,796 kW/m.

Flam length

The analysis of flame length across various vegetation types under varying wind speeds provides critical insights into the dynamics of fire behavior in different environmental conditions. Flame length, a key indicator of fire intensity and potential danger, is directly influenced by factors such as fuel load, fuel moisture, and wind speed. In this study, we observed substantial variations in flame length across different vegetation types, particularly under contrasting wind conditions.

Under a moderate wind speed of 10 km/h, flame lengths were relatively contained, ranging from 2.84 m in degraded shrub, grass, and Aleppo pine regeneration areas to 19.1 m in Aleppo pine forests and wooded shrub areas. The shorter flame lengths in degraded shrub and grass are likely due to the limited availability of combustible material, which restricts the fire's ability to generate long flames. Conversely, the more extensive flame lengths observed in Aleppo pine forests and wooded shrub areas can be attributed to the higher fuel loads and the continuity of fuel, which support sustained and intense combustion.

When the wind speed increased to 23 km/h, there was a notable escalation in flame lengths across all vegetation types. In degraded shrub and grass areas, flame lengths nearly doubled, reaching 5.55 m. This increase underscores the role of wind as a driving force in fire propagation, particularly in areas with lighter fuels that may otherwise burn less intensely. The most significant flame lengths were observed in the Aleppo pine forests and wooded shrub areas, where flames extended up to 24.85 m. This dramatic increase in flame length under higher wind speeds reflects the combined effects of abundant fuel and enhanced oxygen supply, which together contribute to more vigorous fire behavior.

Rate of spread

The ROS is measured in units of distance per time (e.g., meters per minute), reflecting how quickly the fire front advances across various types of vegetation.

At a wind speed of 10 km/h, the rate of spread (ROS) of fire begins at 2.36 units in the least flammable vegetation types, such as areas with sparse or low-density fuel. In these environments, the limited availability of fine fuels and the discontinu-

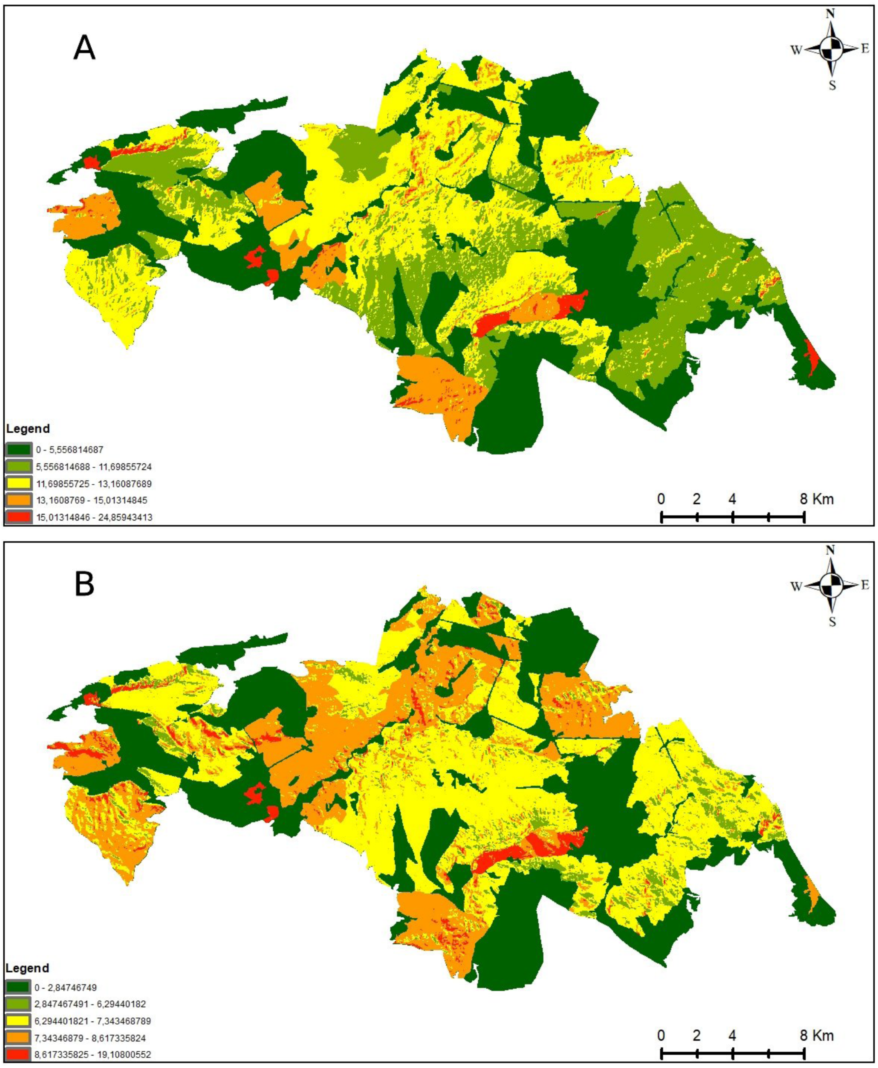

Fig. 3. Flam length under varying wind speed conditions (A: 23 km/h; B: 10 km/h).

ous nature of the vegetation restrict the fire's ability to advance quickly. As the vegetation becomes more continuous and denser, with higher quantities of combustible material such as dense shrub, Aleppo pine forest, and wooded shrub, the ROS increases, reaching 21.56 units in the most flammable areas. This progression reflects the way that fuel availability and continuity play a critical role in determining how fast a fire can move. In denser, more flammable vegetation types, the fire can sustain itself more effectively, leading to faster spread even at moderate wind speeds.

When the wind speed increases to 23 km/h, the ROS escalates dramatically across all vegetation types. In the least flammable areas, the ROS more than doubles to 5.25 units. This sharp increase illustrates how wind acts as a powerful driver of fire behavior, enhancing the fire's ability to preheat and ignite fuels ahead of the fire front, even in less flammable conditions. In the most flammable vegetation types, where fuel is abundant and continuous mainly in wooded shrub and Aleppo pine forest, the ROS skyrockets to 31.16 units. Under these conditions, the fire spreads extremely rapidly, driven by the combined effects of abundant fuel and strong winds that supply oxygen and enhance the fire's intensity.

This significant escalation in ROS with increased wind speed highlights the critical role of wind in wildfire dynamics. As wind speed increases, the fire's ability to spread is exponentially amplified, transforming a moderate fire into a rapidly advancing front that can cover large areas in a short time.

Discussion

The study's results provide a detailed understanding of how fire behavior parameters such as fireline intensity, flame length, and rate of spread (ROS) vary across different vegetation types and under varying wind conditions. However, fire behavior in real scenarios is influenced by a combination of additional factors, including slope, fuel moisture, and the inherent flammability of vegetation types (Khan et al., 2023; Oseghae et al., 2024). These factors can either exacerbate or mitigate the sever-

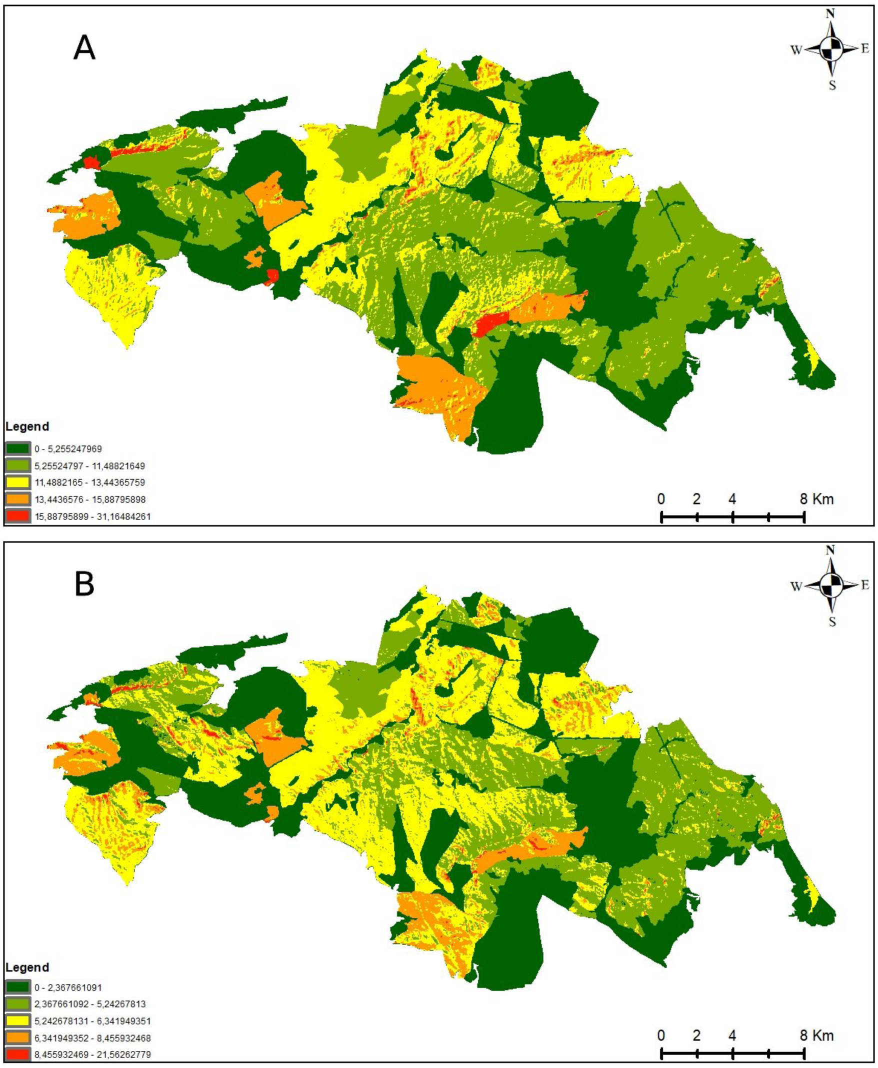

Fig. 4. Rate of spread under varying wind speed conditions (A: 23 km/h; B: 10 km/h).

ity of wildfires, making them crucial considerations in wildfire management and predictive modeling (Sutherland et al., 2023).

Slope is a pivotal factor in wildfire behavior, significantly affecting how fires spread, their intensity, and the resulting flame lengths by altering heat transfer to unburned fuels (Innocent et al., 2023; Shan et al., 2024). In this study, where slopes range from 0 to 35 degrees, the impact on fire behavior across various fuel types is substantial and complex. For example, in grasslands and degraded shrub areas, the rate of spread (ROS) at a 10 km/h wind speed on flat terrain starts at 2.36 units, but this can more than double on a 20-degree slope, pushing ROS to 5.25 units or higher under 23 km/h winds. In more flammable fuel types, such as dense shrublands or Aleppo pine forests, the effects of slope are even more pronounced. On the little slope (0–3°), these areas exhibit a fireline intensity of approximately 697 kW/m, but this figure can escalate significantly on steeper slopes (>30°), potentially exceeding 4,796 kW/m in mixed Aleppo pine and cork holm wooded shrub areas. The impact of slopes on fire behavior varies across fuel types, significantly increasing fireline intensity, especially in more flammable areas (Rodrigues et al., 2023).

Flame length, which is another critical parameter, also shows a marked increase with slope. For instance, in Aleppo pine wooded shrub areas, flame lengths might measure around 8.61 meters at 10 km/h wind speeds on flat ground. However, on an extremely steep slope with increased wind speeds, flame lengths can extend dramatically, reaching up to 24.85 m in this fuel type. This finding is consistent with the results reported by Hassan et al. (2024). This increase not only makes the fires more intense and harder to control but also raises the risk of crown fires, where flames leap into the tree canopies, spreading the fire more rapidly and unpredictably (Guo et al., 2023).

Fuel moisture content is another critical determinant of fire behavior (Boving et al., 2023; Jimenez et al., 2023). High moisture content in vegetation generally leads to lower fireline intensity, shorter flame lengths, and a reduced rate of spread because more energy is required to evaporate the water before the fuel can ignite (Burton et al., 2023). Conversely, dry conditions can lead to an increase in these fire behavior parameters, making fires more intense and difficult to manage (Rao et al., 2023).

For instance, in the degraded shrub and grass areas where the ROS is relatively low (2.36 units at 10 km/h), high moisture content might further slow the fire's spread, reducing the potential for significant fire development. However, in dry conditions, even these areas could become susceptible to rapid fire spread, especially when coupled with high winds and steep slopes.

In more flammable vegetation types, such as dense shrublands and Aleppo pine forests where the ROS is already high, low moisture content can exacerbate fire behavior, leading to extremely high fireline intensities and long flame lengths. Under these conditions, fires can quickly grow in size and intensity, making suppression efforts challenging.

Moreover, the interaction between slope and fuel moisture content further complicates fire behavior. In dry conditions, where fuels are more easily ignited, the influence of slope becomes even more critical. In areas with lower moisture levels and highly flammable vegetation like Aleppo pine, thouja, and dense shrubs, the combined effect of steep slopes and dry conditions can lead to extremely rapid and intense fires (Rodrigues et al., 2023). On the other hand, in less flammable vegetation types such as cork holm and areas with higher moisture content, the impact of slope may be somewhat mitigated, but still significant.

As shown, vegetation type inherently dictates the flammability of the fuel bed, which in turn influences fire behavior (Loudermilk et al., 2022). Certain vegetation types, such as Aleppo pine forests and dense shrublands, have high flammability due to their composition typically involving high levels of fine, dry fuels that ignite easily and burn rapidly (Burton et al., 2023; Mitchell, Martin 2023). This inherent flammability is reflected in the higher ROS, flame lengths, and fireline intensities observed in these areas.

For example, the mixed Aleppo pine, cork holm, and thouja wooded shrub areas exhibit the highest fire behavior metrics under both wind conditions, with ROS reaching 31.16 units and flame lengths up to 24.85 m at 23 km/h. This indicates that these vegetation types not only facilitate rapid fire spread but also contribute to severe fireline intensities and extensive flame lengths, which can lead to large, destructive wildfires.

On the other hand, less flammable vegetation types, such as degraded shrub and grass areas, show lower fire behavior parameters, with ROS as low as 2.36 units and flame lengths of 2.84 m at 10 km/h. However, it is important to note that under extreme conditions such as high winds, steep slopes, and low moisture even these fewer flammable areas can experience dangerous fire behavior, albeit to a lesser extent than their more flammable counterparts.

In addition, when considering the combined effects of slope, fuel moisture, and vegetation flammability, the complexity of wildfire behavior becomes evident. For example, in an area with high flammability vegetation, dry conditions, and steep slopes, even moderate wind speeds could result in a highly aggressive fire that spreads rapidly and is difficult to control. By contrast, in an area with low flammability vegetation, high moisture content, and flat terrain, the same wind speed might result in a much less severe fire, allowing for easier containment. This finding is corroborated by the studies of Loudermilk et al. (2022) and Ghodrat et al. (2022).

The overlay of historical fire data with the results obtained from the current study reveals a clear pattern: the areas that have experienced previous fires are predominantly situated in regions characterized by dense shrub stands and Aleppo pine wooded shrub. This correlation suggests that these vegetation types not only possess high flammability but also contribute to the recurrence of wildfires. Dense shrublands provide a continuous layer of fine fuels that can easily ignite and sustain fire, especially under conditions of low moisture and high wind speeds. Similarly, Aleppo pine wooded shrub areas, with their resinous and combustible material, create an environment conducive to intense and persistent fires. The fact that these regions have a history of burning highlights the need for targeted fire management strategies, such as fuel reduction or controlled burns, to mitigate the risk of future wildfires. By understanding the vegetation types most prone to repeated fire events, land managers can prioritize interventions in these high-risk areas, potentially reducing the frequency and severity of wildfires over time.

Conclusion

The use of FlamMap in this study has provided a detailed understanding of fire behavior across various scenarios, including different wind speeds, and vegetation types. The simulations highlighted the significant impact of these factors on key fire behavior parameters such as fireline intensity, rate of spread (ROS), and flame length. The results demonstrated that high-flammability vegetation, such as dense shrublands and Aleppo pine and thouja wooded areas, are particularly prone to severe fire behavior, with rapid rates of spread and intense flames that are challenging to control.

Given these findings, it is clear that targeted fire management strategies are essential to mitigate the risks posed by wildfires in these high-risk areas. Future efforts should focus on proactive measures such as fuel reduction, especially in areas with dense and highly flammable vegetation. Controlled burns or mechanical thinning could be employed to reduce fuel loads and break up the continuity of vegetation, thereby limiting the potential for large, uncontrollable wildfires.

Additionally, improving early detection and rapid response systems in regions with steep slopes and high-risk vegetation types could significantly enhance firefighting efforts. By prioritizing these areas for monitoring and intervention, it is possible to reduce the frequency and severity of wildfires, ultimately protecting both natural ecosystems and human communities.

Overall, this study underscores the importance of using advanced fire behavior models like FlamMap to inform and guide wildfire management strategies. By continuing to refine these models and integrating them with real-time data and historical fire records, land managers can better anticipate fire behavior and implement more effective fire prevention and suppression tactics.

References

Ahirwar, R.M. (2023). Studies of some techniques for conservation of forest and wildlife. In *Advances in environmental engineering and green technologies book series* (pp. 185–191). DOI: 10.4018/978-1-6684-9034-1.ch006.

AlcAsena, F., Salis, M., Ager, A.A., Castell, R. & Vega-García C. (2017). Assessing wildland fire risk transmission to communities in northern Spain. *Forests*, 8(2), 30. DOI: 10.3390/f8020030.

Benabdeli K. (1996). *Aspects physionomico-structuraux et dynamique des écosystèmes forestiers face à lapression anthropozoogène dans les monts de Tlemcen et les Monts de Dhaya (Algérie occidentale).*Thèse de Doctorat, Faculté des Sciences, Université Djilali Liabès.

Benzina, I., Bekdouche, F. & Bachir A.S. (2024). Post-fire dynamics of recolonization by Cistus plants in the Aleppo pine and Cork oak forests in Bejaia region, central north Algeria. *Environmental & Socio-Economic Studies*, 12(2), 40–47. DOI: 10.2478/environ-2024-0011.

Bitella, G., Bochicchio, R., Castronuovo, D., Lovelli, S., Mercurio, G., Rivelli, A. R., Rosati, L., D'Antonio, P., Casiero, P., Laghetti, G., Amato, M. & Rossi R. (2024). Monitoring Plant Height and Spatial Distribution of Biometrics with a Low-Cost Proximal Platform. *Plants*, 13(8), 1085. DOI: 10.3390/plants13081085.

Bouiadjra, S.E., El Zerey, W. & Benabdeli K. (2011). Étude diachronique des changements du couvert végétal dans un écosystème montagneux par télédétection spatiale : cas des monts du Tessala (Algérie occidentale). *Géographie Physique et Environnement*, 5, 211–225.

Boving, I., Celebrezze, J., Salladay, R., Ramirez, A., Anderegg, L.D.L. & Moritz M. (2023). Live fuel moisture and water potential exhibit differing relationships with leaf-level flammability thresholds. *Functional Ecology*, 37(11), 2770–2785. DOI: 10.1111/1365-2435.14423.

Brunner, I. & Godbold D.L. (2007). Tree roots in a changing world. *Journal of Forest Research*, 12(2), 78–82. DOI: 10.1007/s10310-006-0261-4.

Burton, J.E., Penman, T.D., Filkov, A.I. & Cawson J.G. (2023). Multi-scale investigation of factors influencing moisture thresholds for litter bed flammability. *Agricultural and Forest Meteorology*, 337, 109514. DOI: 10.1016/j.agrformet.2023.109514.

Calvo, R.C., Martínez, M.Á.V., Gómez, F.R., Salamanca, A.J.A. & Navarro-Cerrillo R.M. (2023). Improvements of fire fuels attributes maps by integrating field inventories, low density ALS, and satellite data in complex Mediterranean forests. *Remote Sensing*, 15(8), 2023. DOI: 10.3390/rs15082023.

Cao, X. (2023). Impacts of wildfires and strategies to accelerate secondary succession: A comprehensive analysis. *Theoretical and Natural Science*, 8(1), 263–268. DOI: 10.54254/2753-8818/8/20240418.

Chen, G., Qiu, M., Wang, P., Zhang, Y., Shindell, D. & Zhang H. (2024). Continuous wildfires threaten public and ecosystem health under climate change across continents. *Frontiers of Environmental Science & Engineering*, 18(10). DOI: 10.1007/s11783-024-1890-6.

El Bouhissi, M., Bouidjra, S. & Benabdeli K. (2020). GIS, Forest Fire Prevention and Risk Matrix in the National Forest of Khoudida, Sidi Bel Abbes, Algeria. *Open Journal of Ecology*, 10(6), 356–369. DOI: 10.4236/oje.2020.106022.

El Zerey, W. (2014). Etude diachronique de la régression du couvert forestier de la plaine de Telagh (Algérie): approche par télédétection et SIG. *Bulletin de l'Institut Scientifique Rabat, Section Sciences de la Vie*, 36, 25–31.

Finney, M.A. (2006). An overview of FlamMap fire modeling capabilities. In P.L. Andrews & B.W. Butler (Eds.), *Fuels management – how to measure success* (pp. 213–220). Fort Collins: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Finney, M.A., Brittain, S., Seli, R.C., McHugh, C.W. & Gangi L. (2023). FlamMap:Fire Mapping and Analysis System (Version 6.2) (Software). https://www.firelab.org/project/flammap

Ghefar, M. & Bouazzaoui A. (2021). La vulnérabilité de la forêt de Khodida (W. Sidi bel Abbes) face aux incendies. *Ann. Rech. For.Algérie*, 11(02), 62–67.

Ghefar, M., Morsli, B. & Ayoub B. (2024). Assessing the impact of anthropogenic activities on land use and land cover changes in the semi-arid and arid regions of Algeria. *Environ. Monit. Assess.*, 196, 383. DOI: 10.1007/s10661-024-12524-2.

Ghodrat, M., Edalati-Nejad, A. & Simeoni A. (2022). Collective effects of fire intensity and sloped terrain on Wind-Driven Surface fire and its impact on a cubic structure. *Fire*, 5(6), 208. DOI: 10.3390/fire5060208.

González-Olabarria, J., Rodríguez, F., Fernández-Landa, A. & Mola-Yudego B. (2012). Mapping fire risk in the Model Forest of Urbión (Spain) based on airborne LiDAR measurements. *Forest Ecology and Management*, 282, 149–156. DOI: 10.1016/j.foreco.2012.06.056.

Guo, H., Xiang, D., Zhang, P., Gao, Y., Zhang, Y. & Kong L. (2023). Effects of wind on heat transfer and spread of different fire lines across a pine needle fuel bed. *Combustion Science and Technology*, 197, 782–802. DOI: 10.1080/00102202.2023.2273329.

Hassan, A., Accary, G., Sutherland, D. & Moinuddin K. (2024). Physics-based modelling of wind-driven junction fires. *Fire Safety Journal*, 142, 104039. DOI: 10.1016/j.firesaf.2023.104039.

Innocent, J., Sutherland, D. & Moinuddin K. (2023). Field-Scale Physical Modelling of Grassfire Propagation on Sloped Terrain under Low-Speed Driving Wind. *Fire*, 6(10), 406. DOI: 10.3390/fire6100406.

Jimenez, F., Lorenzo, H., Novo, A., Acuña-Alonso, C. & Alvarez X. (2023). Modelling of live fuel moisture content in different vegetation scenarios during dry periods using meteorological data and spectral indices. *Forest Ecology and Management*, 546, 121378. DOI: 10.1016/j.foreco.2023.121378.

Kalogiannidis, S., Chatzitheodoridis, F., Kalfas, D., Patitsa, C. & Papagrigoriou A. (2023). Socio-Psychological, economic and environmental effects of forest fires. *Fire*, 6(7), 280. DOI: 10.3390/fire6070280

Khan, N., Sutherland, D. & Moinuddin K. (2023). Simulated behaviour of wildland fire spreading through idealised heterogeneous fuels. *International Journal of Wildland Fire*, 32(5), 738–748. DOI: 10.1071/wf22009.

Lopez, A.M., Avila, C.C.E., VanderRoest, J.P., Roth, H.K., Fendorf, S. & Borch T. (2024). Molecular insights and impacts of wildfire-induced soil chemical changes. *Nature Reviews Earth & Environment*, *5*(6), 431–446. DOI: 10.1038/s43017-024-00548-8.

Loudermilk, E.L., O'Brien, J.J., Goodrick, S.L., Linn, R.R., Skowronski, N.S. & Hiers J.K. (2022). Vegetation's influence on fire behavior goes beyond just being fuel. *Fire Ecology*, 18(9). DOI: 10.1186/s42408-022-00132-9.

Mitchell, R.M. & Martin A.R. (2023). Fire, flammability and functional traits at the forefront of global change ecology. *Functional Ecology*, 37(11), 2767–2769. DOI: 10.1111/1365-2435.14432.

Moreno, M., Bertolín, C., Arlanzón, D., Ortiz, P. & Ortiz R. (2023). Climate change, large fires, and cultural landscapes in the mediterranean basin: An analysis in southern Spain. *Heliyon*, 9(6), e16941. DOI: 10.1016/j.heliyon.2023.e16941.

Nasa (2024). https://power.larc.nasa.gov/data-access-viewer/

Nguyen, T.H., Jones, S., Reinke, K.J. & Soto-Berelov M. (2024). Estimating fine fuel loads in Eucalypt forests using forest inventory data and a modelling approach. *Forest Ecology and Management*, 561, DOI: 10.1016/j.foreco.2024.1218.

Oseghae, I., Bhaganagar, K. & Mestas-Nuñez A.M. (2024). The Dolan Fire of Central Coastal California: Burn Severity Estimates from Remote Sensing and Associations with Environmental Factors. *Remote Sensing*, 16(10), 1693. DOI: 10.3390/rs16101693.

Palaiologou, P., Kalabokidis, K., Ager, A. A. & Day M.A. (2020). Development of comprehensive fuel management strategies for reducing wildfire risk in Greece. *Forests*, 11(8), 789. DOI: 10.3390/f11080789.

Pellizzaro, G., Duce, P., Ventura, A. & Zara P. (2007). Seasonal variations of live moisture content and ignitability in shrubs of the Mediterranean Basin. *International Journal of Wildland Fire*, 16(5), 633–641. DOI: 10.1071/WF05088.

Rao, K., Williams, A. P., Diffenbaugh, N. S., Yebra, M., Bryant, C. & Konings A.G. (2023). Dry live fuels increase the likelihood of Lightning-Caused fires. *Geophysical Research Letters*, 50(15). DOI: 10.1029/2022GL100975.

Rodrigues, A., Viegas, D.X., Almeida, M., Ribeiro, C., Raposo, J. & André J. (2023). Fire propagating laterally over a slope with and without an embedded canyon. *Fire Safety Journal*, 138, 103791. DOI: 10.1016/j.firesaf.2023.103791.

Salis, M., Ager, A.A., Alcasena, F.J., Arca, B., Finney, M.A., Pellizzaro, G. & Spano D. (2015). Analysing seasonal patterns of wildfire exposure factors in Sardinia. Italy *Environ. Monit. Assess.*, 187(1), 1–20. DOI: 10.1007/s10661-014-4175-x.

Salis, M., Arca, B., Bacciu, V., Duce, P. & Spano D. (2009). *Assessment of fire severity in a Mediterranean area using FlamMap Simulator.* VIII. Symposiumon on Fire and Forest Meteorology. https://dissem.in/p/37858079

Santos, L.A.C., Brito, T.R.D.C. & De Melo E Silva-Neto C. (2022). Uso dos sistemas de informação geográficas (SIG) nas ciências ambientais: entre 2009 e 2019: uma análise cienciométrica. *Revista Brasileira De Geografia Física*, *15*(4), 1715–1731. DOI : 10.26848/rbgf.v15.4.p1715-1731.

Scott, J.H. & Burgan R.E. (2005). *Standard fire behavior fuel models: a comprehensive set for use with Rothermel's surface fire spread model.* Fort Collins: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Scott, J.H. & Reinhardt E.D. (2001). *Assessing crown fire potential by linking models of surface and crown fire behaviour*. Fort Collins: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. DOI: 10.2737/rmrs-rp-29.

Shan, Y., Gao, B., Yin, S., Shao, D., Cao, L., Yu, B., Cui, C. & Wang M. (2024). Influence of terrain slope on Sub-Surface fire behavior in boreal forests of China. *Fire*, 7(2), 55. DOI: 10.3390/fire7020055.

Sutherland, D., Rashid, M.A., Hilton, J.E. & Moinuddin K.A. (2023). Implementation of spatially-varying wind adjustment factor for wildfire simulations. *Environmental Modelling & Software*, 163, 105660. DOI: 10.1016/j.envsoft.2023.105660.

Taneja, R., Wallace, L., Reinke, K., Hilton, J. & Jones S. (2023). Differences in Canopy Cover Estimations from ALS Data and Their Effect on Fire Prediction. *Environmental Modeling & Assessment*, 28(4), 565–583. DOI: 10.1007/s10666-023-09896-z.

Yavuz, M., Sağlam, B., Küçük, Ö. & Tüfekçioğlu A. (2018). Assessing forest fire Behaviour simulation using FlamMap software and remote sensing techniques in Western Black Sea Region, Turkey. *Kastamonu University Journal of Forestry Faculty*, 18(2), 171–188. DOI: 10.17475/kastorman.459698.

Zagalikis, G. (2023). *Remote sensing and GIS applications in wildfires*. *IntechOpen*. DOI: 10.5772/intechopen.111616.