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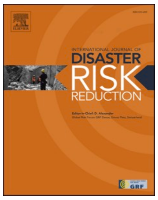

Comparative analysis of wildfire simulation tools: Discrepancies in Rothermel model-based software under varying wind and slope conditions

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ABSTRACT

With the advances in computers and the growth of science in modeling physical phenomena, wildfire simulation software has become an instrumental tool for governments, agencies, and researchers to tackle the growing challenge of wildfires. Various models have been developed using different methodologies, and different software platforms were created using these models. The Rothermel model is one of the most widely accepted and utilized models in simulation software among agencies. This study discusses the differences in numerical results from three widely used software programs that utilize the Rothermel fire propagation model as their foundation. First, each software will be introduced and explained, and their differences will be discussed. In the next step, multiple cases will be defined and simulated with identical inputs using each software. The effects of different slope and wind conditions on the results will be analyzed by designing four simple scenarios. Although it is acknowledged that numerous factors influence wildfire behavior, the analysis demonstrated that just these two factors were sufficient to reveal significant discrepancies among the software. The results of the simulations will be analyzed, and the software will be compared through a discussion. The results show that by increasing the complexity of the scenarios, the difference in results from each software increases. The differences in results between platforms with identical scenarios emphasize that researchers and decision-makers must recognize these variations and exercise extra caution when utilizing wildfire simulation tools for decision-making and operational management.

1. Introduction

Wildfires are often considered either a necessary incident in the cycle of an ecosystem or a natural disaster that can harm lives or worsen habitat conditions, depending on fire intensity, place of occurrence, and impacts. The distinction between these two points of view relies strongly on the main effects of wildfire on human and animal lives, the environment, the ecosystem, and the economy, and

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whether it is expected and managed or not [1]. Wildland fires have been recognized as a crucial field for research by the International Association for Fire Safety Science (IAFSS) Agenda 2030 for a fire-safe world [2]. Over the past decades, an increased number of severe wildfires have occurred due to environmental changes, global warming, and droughts, even in areas not usually exposed to the risk of wildfire, such as the case of Nordic countries [2].

Wildfire simulation and modeling are essential for fire management, as they mitigate risks through fire risk exposure assessment and assist in evacuation planning and management [3]. The ability to forecast wildfire behavior accurately will ensure the safety and effectiveness of wildfire control and fire management [4]. The behavior of wildfires is a complex phenomenon influenced by numerous interrelated factors. This inherent complexity presents challenges when attempting to model and accurately predict wildfire behavior. Factors such as weather conditions, topography, vegetation types, fuel moisture, and human activities all contribute to the dynamic nature of wildfires. The intricate interactions between these variables make it difficult to develop models that capture the full spectrum of wildfire behavior [5,6]. The current wildfire behavior models are limited in their ability to account for all the factors involved. While significant advancements have been made in wildfire modeling, there is still room for improvement to enhance the accuracy and reliability of these models. The challenge lies in accurately representing the complex interactions and feedback loops between various factors. Additionally, the availability and quality of input data also play a crucial role in determining the accuracy of the models. Insufficient or unreliable data can further limit the accuracy and reliability of the predictions [5], [6].

Show [7] conducted the first known field research on fire's rate of spread in the wildlands by documenting the growth of experimental point source fires in northern California from 1915 to 1917. In addition, the first wildfire case study was published by Gisborne [8]. Eventually, more in-depth studies, including field tests, started in Canada and the United States in the 1930s [9,10]. The research in this field gained momentum, and the size of experiments gradually expanded to larger scales by the 1960s [11,12]. Moreover, laboratory experiments with different types of equipment (e.g., wind tunnels) were carried out to better understand the behavior of fire spread in forests [13,14]. The first guide to predicting wildfire behavior was produced by Barrows [15], which was based on analyzing the fire report data as a source of information to estimate the rate of spread.

The next step of research in wildfires was developing numerical solutions and simulations. Wildfire simulation models are distinguished into two basic categories regarding their fundamental approach: physical models and empirical or semi-empirical models. The behavior of fire is defined by both chemistry and physics. The physical model aims to integrate these phenomena into a simulation, enhancing our understanding of the processes that govern fire propagation and behavior. [16]. On the other hand, an empirical model incorporates no physics or chemistry, and the modeling structure is based on statistical data. In addition, some semi-empirical models exist with some form of the physical framework [16]. The actual development of the combustion process is not the aim of empirical or semi-empirical simulations but rather to be used in the management and decision-making process [17]. Many identified a coupling of both approaches as the best solution to simulate better the characteristics of wildfire and fire behavior [18].

Richard Rothermel [19] published a detailed mathematical model of wildfire to predict the fire's rate of spread in wildland fuels, which is the basis of many software. It is one of the most widely used models for predicting fire behavior and serves as the foundation for many modern fire simulation systems. The model is semi-empirical, derived from physical principles, and complemented by extensive experimental data collected from various types of wildland fuel, such as grass, brush, and timber. The model's primary output is the rate of spread of a fire front. Still, it also provides insights into other critical fire behavior parameters such as flame length and fire line intensity. It simplifies the complex dynamics of fire spread by focusing on the energy balance between the heat required to ignite the fuel and the heat generated by the fire. This model could not be used to incorporate the crown fires, while it could only predict the fire's intensity and spread rate in a continuous fuel bed on the ground. Additionally, this model was applicable to bushfires or grasslands since they are considered close to the ground with fuel continuity. As this model does not consider the firebrands as an essential factor in advancing the fire, the effect of firebrands was not considered.

The central equation of the Rothermel model calculates the rate of spread of the fire front using the following formulation:

$$R = \frac{I_R \xi (1 + \phi_w + \phi_s)}{\rho_B . \varepsilon . Q_{ig}} \tag{1}$$

Where: R is the rate of spread (m/s), I_R is the reaction intensity (kW/m^2), ρ_B is the bulk density of the fuel bed (kg/m^3), ε is the effective heating number, representing the fraction of the fuel that is heated to ignition, and Q_{ig} is the heat of pre-ignition (kJ/kg), which is the energy required to bring the fuel to its ignition temperature. $\varnothing_w$ and $\varnothing_S$ are wind factor and slope factor respectively.

The reaction intensity (I_R) is a measure of the energy release rate per unit area and is a function of several factors, including net fuel load $W_n \left(kg / m^2\right)$, the reaction velocity Γ' (1s), and fuel particle heat content h (J / kg). η_M and η_s are accounting for the effects of mineral and moisture content of the fuel respectively. It is given by:

$$I_R = \Gamma' W_n h \eta_M \eta_s \tag{2}$$

The effects of wind and slope are also incorporated in this model. Wind increases the spread rate by bending flames toward unburned fuel, enhancing heat transfer. The effect of wind is modeled through a wind factor ($\varnothing_w$), which is an exponential function of wind speed. Slope ($\varnothing_s$) affects fire spread by altering the angle at which the flames interact with the fuel. Fires tend to spread more rapidly uphill due to the pre-heating of fuels by radiation and convection. The effects of wind and slope are calculated through the following equations:

$$\phi_w = CU_m^B \left(\frac{\beta}{\beta_{op}}\right)^{-E} \tag{3}$$

$$\phi_s = 5.275\beta^{-0.0225}(tg\theta)^2 \tag{4}$$

Where C, B, and E are empirical coefficients that are calculated based on the surface area to volume ratio of the fuel, β and β_{op} are the fuel packing ratio and optimum packing ratio respectively, and θ (radian) is the slope angle.

These equations represent the foundation of the Rothermel model, offering the framework to predict the rate of fire spread under different conditions related to fuel, wind, and topography. This model's outputs were mainly a mean value for the rate of spread and fire intensity, which were obtained following the fuel characteristics and topography of the land as inputs. Nevertheless, the complexity of such models was cast away by the use of visualization and slide-rule devices [20], graphical computation in the form of nomography [21], and the development of computer programs, e.g., Albini, which was one of the most successful [22]. Finally, with the development of such models and programs, computer calculations started their use for operational and research purposes in the field of wildfires in the 1970s [23,24].

The cellular automata (CA) model was another innovative approach that was used by Karafyllidis and Thanailakis [25] for the very first time to predict the fire spread in homogenous and heterogeneous forests (also referred to as the KT model). The advantage of this model was the ability to incorporate weather conditions and land topography. An algorithm was developed based on this model to determine the fire front in some hypothetical forests and showed good agreement with the fire spread in real wildfires. Later on, in an attempt to create software to simulate small-scale fires in the Mediterranean regions, with the scope of fire management and firefighter deployment, Guarsio and Baracani [26] combined the mathematical model introduced by Rothermel for the simulation of fire spread with the CA theory. The cellular automata included two layers: the upper represented the tree crown, and the lower represented the coverage on the surface. Additionally, other affecting factors, such as air temperature, fuel moisture, and terrain slope, were included in the model as coefficients. The effect of wind on the fire shape was considered utilizing Alexander's ellipse theory [27].

Regardless of the model used, three principal factors are pointed out by Albini [21] as the sources of error or disagreement between the acquired results from models and real-life fire behavior data:

1. The model may not be applicable to the situation.
2. The model's inherent accuracy may be at fault.
3. The data used in the model may be inaccurate.

Therefore, applying a model to a situation where it was not intended to be operated could result in significant prediction errors [28]. Through simplification of the relationships, minor factors are neglected, and the model would be based on idealized conditions, which leads to discrepancies between results and the actual fire behavior [29]. Approximations for distinct purposes can be made by observing the fire-modeling laws to increase the data accuracy. Still, it is easily forgotten that they are only approximations, which leads to the tendency to apply models beyond their effective area. For instance, eighteen assumptions are made in Rothermel's crown fire models [30] in the U.S. Northern Rocky Mountains that should be considered and followed through when using the model. Frequent re-examination and redefinition of assumptions on which the models are based, and the range of conditions under which the models are applicable are crucial to avoid these types of errors [29]. Most models that intend to predict the wildfire rate of spread have limiting assumptions and must not be used to simulate what they do not represent [22].

Numerous wildfire spread models assume the fuel complex to be homogenous, continuous, and uniform, which results in variation between predictions and the observed fire behavior. Further research and innovative approaches were used to overcome this issue. Frandsen and Andrews [31] modeled a nonuniform fuel bed forest fire spread, Fujioka [32] applied the non-uniformity to the spatial aspect, and Finney et al. [33] developed a model to calculate the wildfire rate of spread across random landscapes, which eventually led to the development of FARSITE [33]. Additionally, other innovations emerged to address this issue, including Rothermel's two-fuel model concept [34], which was later developed by Martin [35]. Geographic information system (GIS) fire growth models adopted by Beck [36] and Tymstra et al. [37], also aimed to mitigate this problem. Assuming that the fuel bed has only one layer and is adjacent to the ground, neglecting the fire spread by spotting (flying embers), and neglecting the fire spread under the effect of fire whirlwinds are the main assumptions that were the source of variation in results up to that date [22].

Another challenge in modeling wildfires is the accuracy of input data. As mentioned, the behavior of wildfires is affected by parameters such as wind speed and direction, topography, and fuel moisture. Consequently, the predictive simulation models are sensitive to these parameters as inputs. Thus, if input data is not accurate enough or the simulation operator fails to grasp the variation of these parameters over spatial and temporal dimensions, the model results can be biased [22]. The nonlinear nature of wildfire behavior complicates the relation between input and output data accuracy. As a result, the model must establish its input data tolerance over the range of variable values used as input. Therefore, the accurate selection of data inputs remains a challenge for a fire simulation operator, since neither the wind speed nor direction remains constant, nor the topography of the area or even the fuel complex [22].

Drawing on the historical context of wildfire modeling and the associated challenges and limitations, this study aims to provide an overview of the most utilized software for wildfire simulations. Then, by emphasizing the pivotal role of the Rothermel model as a foundational element in wildfire simulation, three widely employed software platforms that rely on this model were selected. The objective is to conduct a comparative analysis by applying a series of identical hypothetical scenarios to these software tools. The effects of varying slope and wind conditions on the results will be analyzed by designing four simple scenarios specifically tailored for this purpose. While it is acknowledged that numerous factors influence wildfire behavior, this study found that just these two factors were sufficient to highlight significant discrepancies among chosen software. Uncovering these discrepancies could be of great value to practitioners, particularly in wildfire management and firefighting. Understanding how different software may produce different outcomes under the same conditions can inform more reliable decision-making and enhance the effectiveness of wildfire response strategies. By conducting these simulations, we underscore the critical importance of exercising caution when utilizing wildfire models. Users, policymakers, and researchers must recognize that each model has its own set of limitations and should be employed within their respective boundaries. This awareness is crucial for the responsible and effective use of wildfire simulation tools in decision-making and operational contexts.

2. Wildfire simulation software

As previously discussed, fire models are classified into three broad types: empirical, semi-empirical, and physical [38]. Empirical models are solely based on statistical correlations derived from experimental data and do not include the physical phenomena of the fire. Semi-empirical models include the energy conservation equation but do not differentiate between heat transfer modes, i.e., radiation, convection, and conduction. Theoretical methods or physics-based models attempt to solve all the governing equations (fluid dynamics, heat transfer, and combustion) with reasonable assumptions and approximations [6].

BEHAVE [39] was one of the first and most widely used wildfire simulation software, which was developed from the works of Frandsen [40] and Rothermel [19]. This model is classified as semi-empirical because it is based on a simple energy balance between the energy required to sustain fire spread and the energy received by unburned fuel. Later, BEHAVE was coupled with geographical information systems (GIS), including the terrain slope and fuel characteristic at a landscape scale, and became a part of the propagation model of FARSITE [33], an operational system used by the US government.

FARSITE is a software designed to be used by land and fire managers on personal computers (PC). This software uses Huygens' principle of wave propagation to expand fire fronts. This principle enables FARSITE to implement existing fire models, i.e., surface fire spread by Andrews [39] and Rothermel [19], transition to crown fire, crown fire spread by Rothermel [30] and Van Wagner [41,42], and spotting distances [43,44], in a logical manner. Weather forecast difficulties and the absence of 3-dimensional wind flow in the complex terrain were identified as the primary sources of error for this model by its developers [33]. Nevertheless, this model had other limitations as sources of error and uncertainty. Difficulty in defining an appropriate fuel model, in addition to the validity domain of

Table 1
Summary of software platforms.

Software	Model Type	Key Features	Limitations	Availability	Computation Intensiveness
BEHAVE	Semi-empirical	- One of the first computational formulations of the Rothermel model and would result in fire spread values - Simple energy balance model; - Later coupled with GIS for landscape-scale simulations	- Lacks complex terrain and wind modeling; - Difficulties in defining appropriate fuel models - Does not account for crown fires, spotting, or fire-atmosphere interactions	- Free, publicly available	- Low; - suitable for desktop use.
FARSITE	Semi-empirical	- Uses Huygens' principle for fire front expansion; - Includes surface fire spread, crown fire transition, and spotting distances	- Weather forecast difficulties; - Absence of 3D wind flow	- Free, publicly available	- Moderate; - desktop use with GIS integration
FlamMap	Semi-empirical	- Non-temporal fire spread simulation - Primarily used for risk assessment of the fire conditions of an area under specific conditions	- Absence of 3D wind flow - Lack of fire-atmosphere interactions - Weather does not vary with time	- Free, publicly available	- Moderate; - desktop use with GIS integration
SPARK	Semi-empirical	- Uses level set method; - Integrates various fuels using gridded inputs - High flexibility for defining fire spread models	- Lack of predefined models - Advanced Knowledge requirement for setup and simulation	- License required; - Free to use for research purposes	- Moderate
FIRESTAR	Physics-based (2D-implicit)	- Includes multiphase combustion model; - Accounts for both radiation and convection; - Suitable for small-scale simulations	- Limited by 2D assumptions; - Less suitable for large-scale simulations	- Research use; typically, not available to the public	- High
FIRETEC	Physics-based (3D-explicit)	- Suitable for large-scale simulations; - Includes 3D numerical solution; - Various fuel types included	- Limited combustion model (no transport phase)	- Research use; typically, not available to the public	- Very High
FIRELES	Physics-based (3D-explicit)	- Suitable for small-scale simulations; - Includes explicit 3D numerical solution; - Simulates multiphase combustion	- Limited to small scales; - Does not support multi-fuel modeling - No turbulence radiation interaction model	- Research use; typically, not available to the public	- Very High

empirical coefficients introduced to the model, was identified by Morvan [45] as the flaws in this system that led to its relative lack of success. Finney introduced **FlamMap** [46], a more developed software that included FARSITE and other models. FlamMap can simulate wildfire propagation and behavior for more extended periods under various fuels, fuel moisture, weather, and terrain conditions.

Miller et al. developed **SPARK** [47], a prediction tool that simulates fire propagation over a domain according to an algebraic rate of spread by using the level set method. Spark can integrate a variety of fuels by using gridded inputs for fuel properties. Other parameters, including atmospheric conditions, fuel conditions, topography, and ignition location, are considered using different data sets.

Nevertheless, the evaluation of empirical parameters using experimental tests on laboratory scale and extending their results to large-scale wildfires can be misleading [45]. Treating parameters, such as wind, slope, and the fraction of the energy received by the fuel, on the dynamics of fire with an empirical or semi-empirical approach could result in biased results. Even in particular cases, these models can produce unacceptable results, such as rate of spread greater than the wind speed [6,48]. This approach considered radiation as the primary way of heat transfer between fire and unburned fuel and ignored the role of convective heat transfer from the hot gases pushed forward by the wind to the fuel up ahead [49]. Therefore, the necessity of physics-based models came into appearance.

The development of physical models is due to the fast improvement in computational fluid dynamics (CFD) science for modeling turbulent and reactive combustive flows over the past decades [45]. Lopes et al. introduced **FIRESTAR** [50], a 2-dimensional implicit numerical solution of the physical wildfire model developed at the University of Aix-Marseille. FIRESTAR included the multiphase combustion model with the interaction of radiation and convection at the same time, and different types of fuel were considered. This package was mostly suitable for small-scale situations, and by considering the limitations of 2D assumptions, it can be used for large-scale situations [45,50].

FIRETEC [51] is a model that could only be used for large-scale simulations with a 3D numerical solution of the governing equations. This model included different fuel types, but the combustion model was limited to pyrolysis, and combustion at one location without a transport phase [6]. In contrast, **FIRELES** is a model that is only suitable for small scales, utilizing an explicit 3D numerical solution of the governing equations. This software simulates the combustion in a multiphase situation but does not include a multi-fuel modeling ability [45]. Table 1 presents a summary of the presented platforms.

Since other works comparing and analyzing the previously mentioned software already exist, for example, the works of Bova [52], Mell et al. [6], Sullivan [53], Morvan [45], Papadopoulos and Fotini-Niovi [17], and Cruz et al. [5], Fox-Hughes et al. [54], FireStation (FS), Fire Dynamic Simulator (FDS), and Wildfire Analyst (WFA) are chosen for this study. Even though there are published papers and manuals for the software, each software's model, their inputs, the input/output formats, and their different features will be explained briefly in the following chapter according to their published works, so that the reader can have an understanding of each software.

3. Methods

The software tools used in this study, FireStation, Wildfire Analyst, and Fire Dynamic Simulator, all use the Rothermel surface fire propagation model [19]. However, divergence exists among the various sub-models employed by these tools, particularly regarding factors like fire shape and wind dynamics. This variability influences how the software responds to different scenarios, making comparative analysis crucial for understanding their respective capabilities and performance differences. This study seeks to provide valuable insights into the specific advantages and limitations of various software tools by examining how they incorporate and apply the foundational principles of the Rothermel model while differing in their sub-models. Ultimately, this will yield a comprehensive evaluation of their overall effectiveness in wildfire modeling.

This chapter provides an overview of the three selected wildfire modeling software. This chapter also covers the input and output formats for each software, providing insight into the particular data preparation requirements. Furthermore, the companion software required for their proper operation is identified.

1. FireStation (Version 1.0.16)

FireStation is a software designed to simulate the fire spread over complex topography. The modeling of the wind field over the terrain employs two separate models. Both models base their wind predictions on local observations made at meteorological stations, including wind speed and direction. The coupling effect of the wind field with the fire can be simulated using one of the wind prediction models [55].

In the year that FireStation was released, it was claimed that no previous wildfire simulation software (to the developers' knowledge) incorporated any type of model for wind field calculation other than FireStation. Another claimed feature of this package was the software's user-friendliness, not only towards the input parameters but also regarding the results and output comprehensiveness. FireStation contains an interface based on the Windows command system, on top of the mathematical models for fire and wind simulation. This enables the user to grasp a simple understanding of the required inputs and resulting outputs [55].

FireStation uses Rothermel's surface fire spread model [19] for the fire behavior and rate of spread. The Rothermel model is compatible with different fuel models, which makes it a suitable choice for many wildfire simulation software. Nevertheless, the Rothermel model only provides the rate of spread toward the maximum spread direction, and it is not enough to simulate the fire propagation and burning area. Another model to anticipate the fire shape is also required, for which the FireStation uses the Anderson model [56] and the Alexander model [27]. The input for the fire shape model is the wind speed at mid-flame height.

For the wind field simulation, a significant feature of this software, FireStation implements two models: NUATMOS and CANYON.

NUATMOS is a linear model, developed by Ross et al. [57], which solves the continuity equation in a three-dimensional grid. This model takes the wind speed and direction as its input, and as the first step inserts interpolation/extrapolation estimate values of the wind field into all grid points, which later are adjusted using a variational analysis method until it reaches a divergence-free flow field to satisfy the continuity equation. The result's accuracy could be increased by increasing the number of wind observation points in the study area. Despite the limitations of this model, posed by the fact that it cannot simulate the buoyancy and separation phenomena, the solutions provided are quite realistic in most cases, and the simplicity of the code and short computation times, make this model quite favorable.

The second model available in FireStation for wind field simulation is CANYON, a model developed by Lopes et al. [58] that solves the three-dimensional Navier-Stokes equation in addition to the continuity equation. The effects of turbulence on the flow field are incorporated with the k-Ɛ model, and the effects of terrain or vegetation roughness and thermal effects of fire on the flow field are also accounted for.

2. Wildfire Analyst (Version 2.9)

Wildfire Analyst is developed by Technosylva, with the primary objective of using it in real-time or on-field operations. This software is designed to have flexibility toward predefined scenarios, which include fuel maps, vegetation, and weather. This feature eliminates the need to integrate data every time the software is being used, which can save time. Wildfire Analyst enables the user to access GIS data directly from the platform since it is based on ArcGIS*TM* [59].

This software uses the model developed by Rothermel [19] with the modifications proposed by Albini [21]. In addition to the Rothermel and Albini fuel models, the Scott and Burgan [60] fuel model is used, with the ability to incorporate other custom fuel models. The fire evolution is a single ellipse, using the Anderson [56] model with the approach presented by Finney [46] in Farsite. Crown fires can also be simulated, based on the models developed by Rothermel [30] and Wagner [41]. Moreover, the Kitral model [61], an empirical fire propagator model developed by the University of Chile and INTECCHILE, is also available in Wildfire Analyst.

The simulation is capable of integrating various semi-empirical models thanks to a robust set of equations that describe fire characteristics influenced by multiple factors, including weather, topography, fuel type, fuel moisture, and the presence of firebreaks. Furthermore, it offers several modes for fire management that authorities can employ, such as probabilistic mode, reverse time simulation, and evacuation timing [59].

For the simulation of the wind field, WFA uses WindNinja, which is an independent software. WindNinja uses the model developed by Forthofer [62,63]which is a 2D High-resolution wind system. The temperature of the surface is integrated into the calculations through the coupling of the energy equation.

Wildfire Analyst offers a range of innovative tools that can enhance fire management and planning. The *Exposure Analysis* tool is based on the minimum travel time concept proposed by Finney [64]. This tool calculates the time fire needs to reach a certain point of interest under a specific situation (Fuel, topography, and wind). This mode can be instrumental in creating defensive measures for communities against wildfires.

3. Fire Dynamic Simulator (Version 6.8.0–1246)

Fire Dynamic Simulator is a CFD model for fire-driven flows, developed by the National Institute of Standards and Technology of the United States. The Navier-Stokes and chemical reaction equations are solved numerically for flow fields with a Mach number below 0.3. FDS is based on FORTRAN and does not have an interface. Input data must be provided through a text document that defines the domain and the required outputs specified by the user. FDS reads the input from this document, numerically solves the governing equations, and presents the user-defined outputs in various files. It also has a companion software called Smokeview, which features a graphical interface that generates results in the form of animations [65].

Three different methods can be used to simulate a wildland fire using FDS.

- Modeling the vegetation or fuel using a set of particles that can be heated through convection or radiation.
- Modeling the vegetation or fuel as a porous solid with a thickness equal to vegetation height.
- Modeling the fire propagation using empirical methods and level set model.

The first two methods use physical models to simulate the fire. They require a very fine mesh grid and require high computation resources. Only the third method will be explained, as the first two are not relevant to this work.

Level set models are suitable for scenarios on a large scale, in which the study area cannot be gridded finely enough to use a physical model. The fire front propagation model is based on the model used in FARSITE by Finney [33], which are models of Rothermel [19] and Albini [21,22] and the fire shape of a single ellipse modeled by Richards [66]. The fuel family model used in FDS is the 13-fuel family presented by Rothermel [19] and Albini [21,22] with the ability to introduce custom fuels if necessary.

Four level set modes [52] with different features are available that should be selected according to the requirements from the simulation. The first mode only simulates the surface propagation model without simulating the actual fire, and the wind is applied globally to the domain without being affected by the terrain. The second mode develops the wind field over the terrain before the ignition time and remains the same (frozen) when the propagation starts. The third mode develops the wind field over the terrain dynamically throughout the whole simulation time, but there is still no actual fire. In the level set mode number 4, the wind field is affected both by the terrain and the fire, by calculating the heat release rate per unit area and coupling the energy equation with the

Navier-Stokes solver [65].

Several third-party software is available to help the users create the text document input file for FDS. For wildfire simulation on a large scale, the qgis2fds plug-in from QGIS Desktop (v. 3.30.3) which is a GIS software will be used.

3.1. Software setup and customization

Each selected wildfire simulation software package requires a unique setup and input data format. Understanding these requirements is crucial for effectively utilizing the software.

The key factors that software needs to simulate wildfire behavior include the fuel map, fuel model, terrain elevation, weather conditions, and particularly wind speed and direction. This text will explain these inputs in detail and discuss the necessary customizations and edits required for effective simulation.

The simulation's fuel component is comprised of two essential factors: the land cover or fuel map and the fuel model. In the context of this study, which involves the simulation of 4 hypothetical scenarios, focus is made on the manual generation of fuel maps. Crafting these maps manually ensures a tailored scenario to compare the software function based on controlled and identical criteria. Turning to the fuel model, all three software platforms utilize the 13-fuel family model introduced by Rothermel-Albini [19,21], establishing a common framework for characterizing fuel types. However, despite the uniform adoption of this model, subtle differences exist among the default settings in the software tools. Minor variations in factors such as the heat of combustion, fuel moisture content, fuel height, and units, impact the simulation outcomes. Thus, while a shared fuel model provides a basis for comparability, researchers should consider these default discrepancies when interpreting and comparing simulation results across different software platforms. While landcover and fuel models are essential inputs for wildfire simulation across all software packages, it's crucial to note that each software requires a different format and preparation method.

In considering topography elevation for wildfire modeling, it is essential to note that FireStation and Wildfire Analyst require raster data for practical representations. However, the needed formats for these raster files are different, complicating the data preparation procedure. On the other hand, the Fire Dynamic Simulator (FDS) presents a challenge because it only accepts text commands as input, making direct usage of raster files impossible. To bypass this constraint, an important intermediate step is to use QGIS software's qgis2fds utility. This utility converts raster files to the required text command format for FDS, allowing for the incorporation of terrain elevation data into the simulation. A similar approach applies to FDS for the fuel map. This method guarantees that terrain and fuel data are correct and consistent across all three simulation tools. Both the fuel map and elevation model were created manually in consistent formats and resolutions, similar to the data sources provided by national and international agencies, to avoid any bias that may arise from differences in resolution or format.

Integrating wind dynamics into simulations highlights inconsistencies in implementation across FireStation, Wildfire Analyst, and Fire Dynamic Simulator, as outlined in their respective software descriptions. To ensure a fair comparison, we selected only wind modes that provide the most consistent application across these platforms. Specifically, the global wind application in Wildfire Analyst—which includes the use of wind adjustment factors for the entire simulation domain—was aligned with Level Set 1 in Fire Dynamic Simulator. Meanwhile, NUATMOS in FireStation corresponds to Level Set 3 in Fire Dynamic Simulator. Despite these efforts to standardize wind application, discrepancies persist due to the inherent differences in the models employed by each software. Such variations may result in differing outcomes when testing identical scenarios.

3.2. Test case scenarios

The test case scenarios for this study, as presented in Table 2, were methodically designed to follow a systematic progression, beginning with the simplest possible scenario and gradually adding more complications. The starting scenario has flat terrain, a single fuel type, and no wind. Subsequent versions gradually introduce one more component at a time, allowing for examination of the software's responses to increasing complexities. In addition, the Rothermel [19] rate of spread and Anderson [56] double ellipse fire shape equations were solved manually as direct analytical solutions. The outcomes from the software platforms are compared to the analytical results of the equations. This structured methodology allows for a comprehensive investigation of how each program responds to incremental changes in environmental parameters, revealing information on the software's sensitivity and dependability in capturing the dynamics of wildfire behavior under different situations.

The decision to use only one type of fuel in this study is based on the need for a controlled and systematic evaluation of wildfire simulation software. By maintaining the same fuel type in all situations, we can better isolate the effects of other factors such as wind and geography on fire behavior. This deliberate simplicity allows for a more focused assessment of how each program responds to varying environmental conditions while keeping the fuel type constant. Introducing multiple fuel types could add unnecessary

Table 2
List of test case scenarios.

Scenario	Wind (m/s)	Terrain Slope (degree)	Fuel Model
1	0	0	1
2	0	5, 10, 15	1
3	1, 2	0	1
4	1, 2	5, 10, 15	1

complexity, making it challenging to determine whether differences in results are due to variations in the fuel model or other factors. However, exploring the effects of different fuel types could be a valuable topic for future research.

All simulations across different scenarios were consistently conducted over a 10-h burning period with a mesh size of 25 m. The choice of a 10-h burning period is in line with wildfire incident norms, as it captures the average duration of fire incidents. Additionally, a mesh size of 25 m was selected to reflect the typical grid size used for input data, which includes fuel maps and terrain elevation. This grid size ensures that the simulations are based on realistic and relevant spatial information, thereby enhancing the accuracy and applicability of the results to real-world situations for practitioners.

In this study, simulation results are compared based on four key metrics: the maximum spread length from the ignition point, the head-to-back length of the burnt area, the total burnt area, and the burnt area perimeter, chosen for their significance in capturing various elements of wildfire behavior. The maximum spread length indicates the rate and extent of fire propagation, while the head-to-back length reveals the overall shape and geometry of the burnt area. Additionally, the total burnt area encompasses both intensity and geographic coverage, while the burnt area's perimeter refines our understanding by considering boundary features. Moreover, from a practical and managerial perspective, these parameters are vital for evaluating fire intensity and spatial extent, aiding strategic decision-making in fire management and mitigation. By comparing these aspects, the study aims to provide insights into how simulation results from different tools influence operational and management choices, improving decision support systems for more informed and adaptive wildfire response and mitigation measures. In addition to the metrics illustrating wildfire behavior, the required run-time for each simulation is a vital component of the results presentation. Recognizing the practical implications for operational and management applications, the time efficiency of the simulation process is crucial. The integration of run-time data is critical for stakeholders and decision-makers who value both the accuracy of simulation and the speed with which these results may be received for timely and adequate decision-making. The variation of runtimes of the software platforms was compared to FireStation's runtime as this platform took less time among all three.

The results measurements for Wildfire Analyst and FireStation were conducted using GIS software (Arcmap v. 10.8.1) measurement feature, leveraging their provision of raster file data for output. However, considering FDS's unique output format, which does not include raster files, an image processing software (FIJI v. 1.54g) was used to measure the required parameters. This technique enabled the extraction and analysis of needed metrics from FDS simulations, resulting in a consistent and thorough evaluation of all three software packages.

4. Results

The wildfire simulations performed in this study include 42 simulations from four scenarios, run across the three software platforms plus 12 direct analytical solutions.

4.1. Scenario 1

Scenario 1 represents the baseline simulation with no wind, flat terrain, and a single fuel type (Table 3).

The results for Scenario 1, which represents the most basic modeling scenario, are almost equal across FS, WFA, and FDS. In theory, under such simplified conditions, the simulation results should be identical. However, small discrepancies in reported metrics can be due to intrinsic measurement errors or computational subtleties within each software. Despite these minor variances, the overall results show a high level of consistency among the three tools in capturing key fire behaviors. Taking the results from the direct analytical solution as a point of reference, the variation of results is presented in Table 4.

To improve the comprehension of the simulation results, each scenario will also be visually represented (Fig. 1).

4.2. Scenario 2

The next phase of the simulations included an aspect impacting the rate of spread behavior: terrain slope. In this situation, three cases were examined, each with a different slope angle. The goal was to determine how terrain slope influences wildfire behavior and fire shape in each software. The results of these simulations are given in Table 5, revealing the subtle interaction between terrain slope and the observed rate of spread behavior across the software tools used.

Table 6presents the percentage variations relative to the direct analytical solution in Scenario 2, highlighting the sensitivity of simulation results across different software. As terrain slope increases, discrepancies between the software also increase. The variation follows a sub-linear trend for Max Spread and Head to Back for WFA and linear for FS, a super-linear trend for Burnt Perimeter and Burnt Area, and a primarily linear trend for FDS results. This emphasizes the critical influence of slope on fire spread behavior, where

Table 3
Scenario 1 simulation results for a 10-h burning period.

Software	Max Spread (m)	Head to Back (m)	Burnt Perimeter (m)	Burnt Area (ha)	Runtime (s)
Analytical	1080	2160	6786	366.4	–
FireStation	1080	2125	8073	349.8	1
WFA	1075.	2122	8210	332.2	38
FDS	1059	2107	6843	346.1	1090

Table 4
Variation % results of scenario 1.

Software	Variation (%) Max Spread	Variation (%) Head to Back	Variation (%) Burnt Perimeter	Variation (%) Burnt Area	Variation (100 %) Runtime
FireStation	0.04	−1.6	19	−4.5	–
WFA	−0.4	−1.7	21	−9.3	37
FDS	−1.9	−2.5	0.8	−5.5	1089

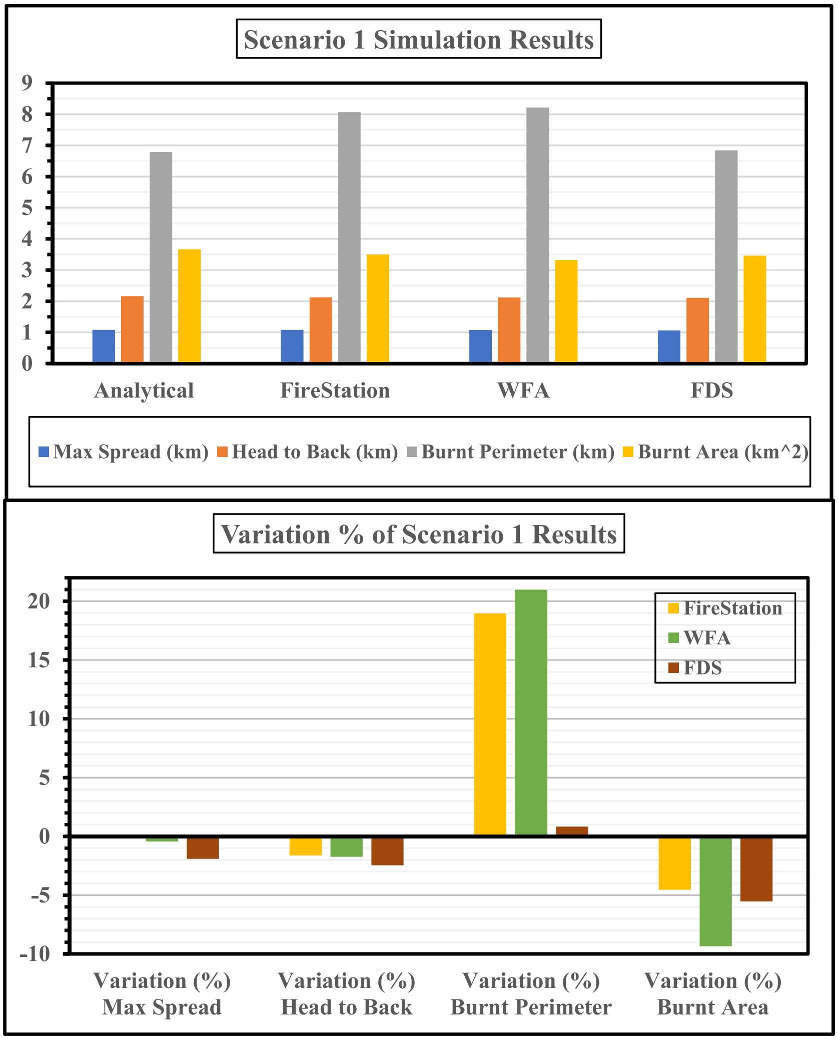

Fig. 1. Results and their variation of scenario 1 simulations.

even slight model differences can lead to deviations in wildfire predictions(see Fig. 2).

4.3. Scenario 3

Scenario 3 regresses to flat terrain but provides a new variable by including wind in the simulations. This time, the flat terrain simulations are run with two different wind speeds: 1 and 2 m/s. The addition of wind as an element intends to investigate how various wind velocities affect the pace of spread behavior in wildfire simulations. The results of these simulations, now considering the interaction of wind and flat terrain, are presented in the following table.

The Variation of the results of scenario 3 cases is presented in the Tables 7 and 8.The results are visually presented in Fig. 3.

Table 5
Scenario 2 Simulation Results for a 10-h burning period.

Slope Angle (deg)	Software	Max Spread (m)	Head to Back (m)	Burnt Perimeter (m)	Burnt Area (ha)	Runtime (s)
5	Analytical	1420	2039	5458	225.2	–
	FireStation	1400	2002	5362	208.1	1.8
	WFA	1303	1748	5069	199.1	30
	FDS	1401	2219	6828	370.8	2439
10	Analytical	2459	3292	8812	586.2	–
	FireStation	2379	3302	8609	544.6	0.67
	WFA	2149	2627	7912	400.3	24
	FDS	2381	3387	10,252	834.2	2414
15	Analytical	4265	5737	15,054	1674.5	–
	FireStation	4025	5418	14,023	1420	8.4
	WFA	3570	4148	11,361	926.9	66
	FDS	4180	5495	16,291	2103.9	7392

Table 6
Variation % of scenario 2 results.

Slope Angle (deg)	Software	Variation (%) Max Spread	Variation (%) Head to Back	Variation (%) Burnt Perimeter	Variation (%) Burnt Area	Variation (100 %) Runtime
5	FS 5°	−1.4	−1.8	−1.7	−7.63	–
	WFA 5°	−8.2	−14.2	−7.1	−11.6	15.6
	FDS 5°	−1.3	8.8	25.1	64.6	1354
10	FS 10°	−3.2	0.3	−2.3	−7.1	–
	WFA 10°	−12.6	−20.2	−10.2	−31.7	35
	FDS 10°	−3.2	2.9	16.3	42.3	3603
15	FS 15°	−5.6	−5	−6.8	−15.2	–
	WFA 15°	−16.3	−27.7	−24.5	−44.6	6.9
	FDS 15°	−2	−4.2	8.2	25.6	879

4.4. Scenario 4

In the last part of the study, the simulated cases were extended to include the combined impacts of wind and terrain slope. The scenarios included terrain slopes of 5, 10, and 15°, together with wind speeds of 1 and 2 m/s directed up the hill. This comprehensive method sought to represent the subtle interplay between wind dynamics and changing topography, while also addressing their combined influence on wildfire behavior. This scenario was created to analyze the variance in results when two factors combine and influence wildfire behavior. The findings of these situations are shown in the following table (see Table 9, Fig. 4).

Table 10 presents the percentage variation of results for Scenario 4 simulations.

To better understand the simulated fire behavior across different software platforms, the final burnt area for each simulation is presented. The addition of this metric helps to analyze the simulation results and assess the usefulness and accuracy of each software's fire behavior predictions. The fires were initiated using a point as ignition, and for scenarios 2 through 4 the direction of wind and slope is indicated (East).

Significant differences were observed in the fire propagation while obtaining the results from FDS using level 3 for Scenario 4. These differences were particularly pronounced at higher wind speeds. Upon investigating the cause of this issue, it was discovered that the development of the wind field over the slope became lateral rather than parallel to the slope. The interaction of the wind with the terrain created circulation in the lateral directions, which in turn caused the fire to spread perpendicular to the slope. Due to these issues occurring with the use of level set 3 in FDS, the results from this mode were removed from the comparison to ensure accuracy and reliability in the analysis. The fire shapes from this case are presented in Fig. 9, and they will be discussed in the discussion chapter.

5. Discussion

This study aimed to compare the performance of three fire simulation tools—FireStation, Wildfire Analyst, and Fire Dynamics Simulator—all built on the same foundational surface fire spread model for fire behavior and fuel characteristics. The goal was to understand how these tools behave in simple scenarios and identify potential variations in results that might affect more complex, real-world situations.

The study's robustness was enhanced by efficient software input and configuration setup, which followed the standard format offered by the government or international agencies for data such as fuel maps and digital elevation models. The adoption of standard, open-access formats for inputs aimed to reduce any biases caused by differences in data sources, resulting in a fair and credible comparison.

In the first scenario, simulation results showed that all software tools produced similar results in the simplest case (see Fig. 5). This validates the foundation models used, emphasizing their ability to deliver consistent findings when simulation complexity is reduced.

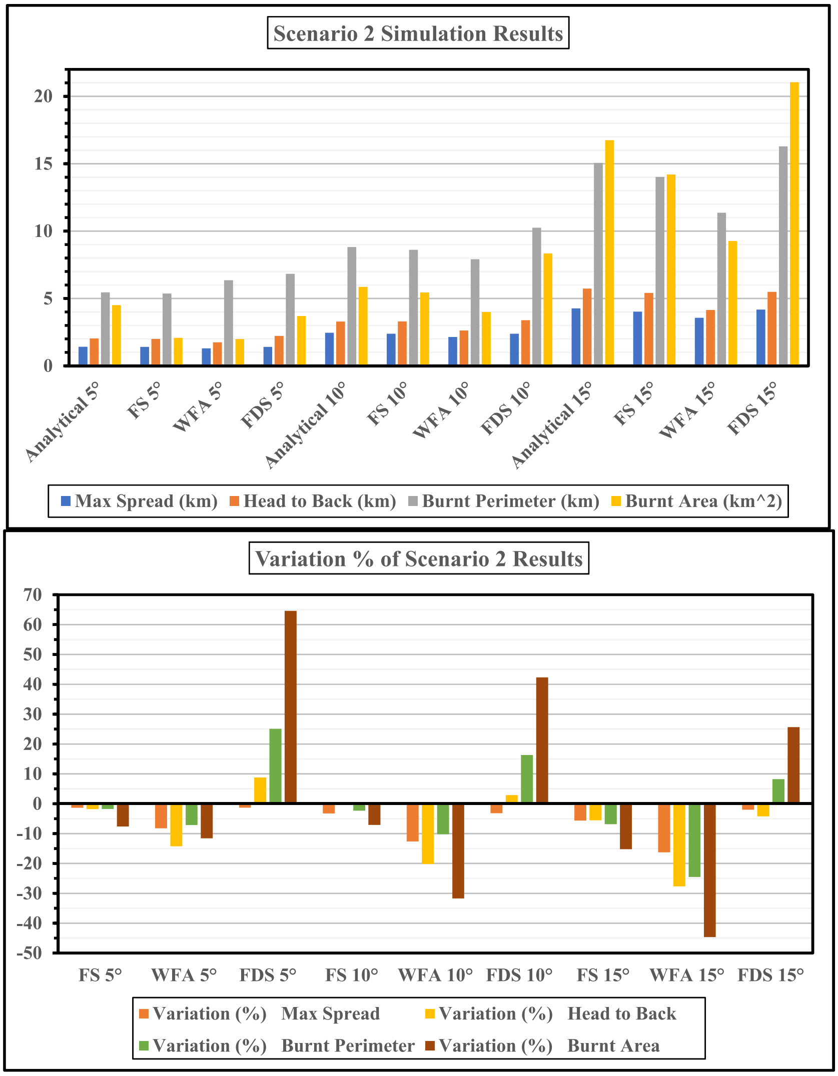

Fig. 2. Results and their variation of scenario 2 simulations.

Table 7
Scenario 3 simulation results.

Wind (m/s)	Software	Max Spread (m)	Head to Back (m)	Burnt Perimeter (m)	Burnt Area (ha)	Runtime (s)
1	Analytical	1735	2458	6545	322.8	–
	FireStation	1568	2253	7581	256.7	49
	WFA	1598	2048	6562	258	156
	FDS (lvl1)	1645	2433	7369	431.1	681
	FDS (lvl3)	1741	2548	7697	470.5	39322
2	Analytical	3832	5187	13,569	1.357.7	–
	FireStation	3161	4326	12,011	909	53
	WFA	3273	3817	10,330	783	170
	FDS (lvl1)	3348	4519	13,321	1403.1	1252
	FDS (lvl3)	3403	4645	14,514	1443.1	61299

However, when scenarios expanded to include more elements like slope and wind, the differences in results grew more obvious. Despite close maximum spread values, variances in fire form, as determined by the software's fire shape sub-models, resulted in considerable discrepancies in the final burned area. This underscores the need to consider other indicators in addition to maximum spread when conducting a comprehensive evaluation.

The final scenario, which combined wind and slope parameters, revealed significant variances in results. Although the scenario was

Table 8
Variation % of scenario 3 results.

Software	Wind Speed (m/s)	Variation (%) Max Spread	Variation (%) Head to Back	Variation (%) Burnt Perimeter	Variation (%) Burnt Area	Variation (100 %) Runtime
FS	1	−9.6	−8.3	15.8	−20.5	–
WFA		−7.8	−16.7	0.3	−20.1	2
FDS (lvl-1)		−5.1	−1.0	12.6	33.5	13
FDS (lvl-3)		0.4	3.6	17.6	45.7	801
FS	2	−17.5	−16.6	−11.5	−33.0	–
WFA		−14.6	−26.4	−23.9	−42.3	2
FDS (lvl-1)		−12.6	−12.9	−1.8	3.3	22
FDS (lvl-3)		−11.2	−10.4	6.9	6.3	1155

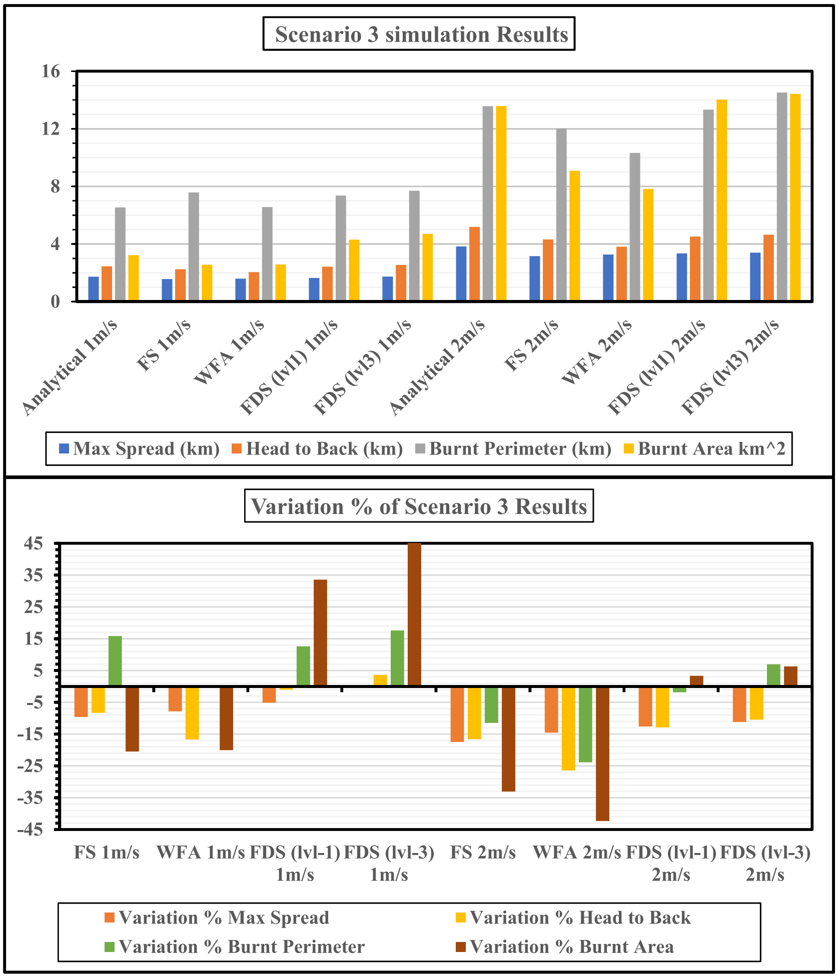

Fig. 3. Results and their variation of scenario 3 simulations.

relatively basic compared to real-world scenarios, the combination of wind and slope highlighted the complexity and sensitivity of fire behavior models, revealing the software tools' different responses to these interacting aspects. It is worth noting that the findings from scenario 4, done by FDS on level-set 3, were removed owing to unrealistic wind behavior in lateral directions, resulting in turbulence and lateral fire propagation. This demonstrates the limitations of particular setups and the importance of careful analysis when combining specific factors. Additionally, the time required for simulations emerged as a crucial practical consideration. FDS, being significantly time-consuming (hours or days compared to minutes for FireStation and Wildfire Analyst), is more suited for investigative

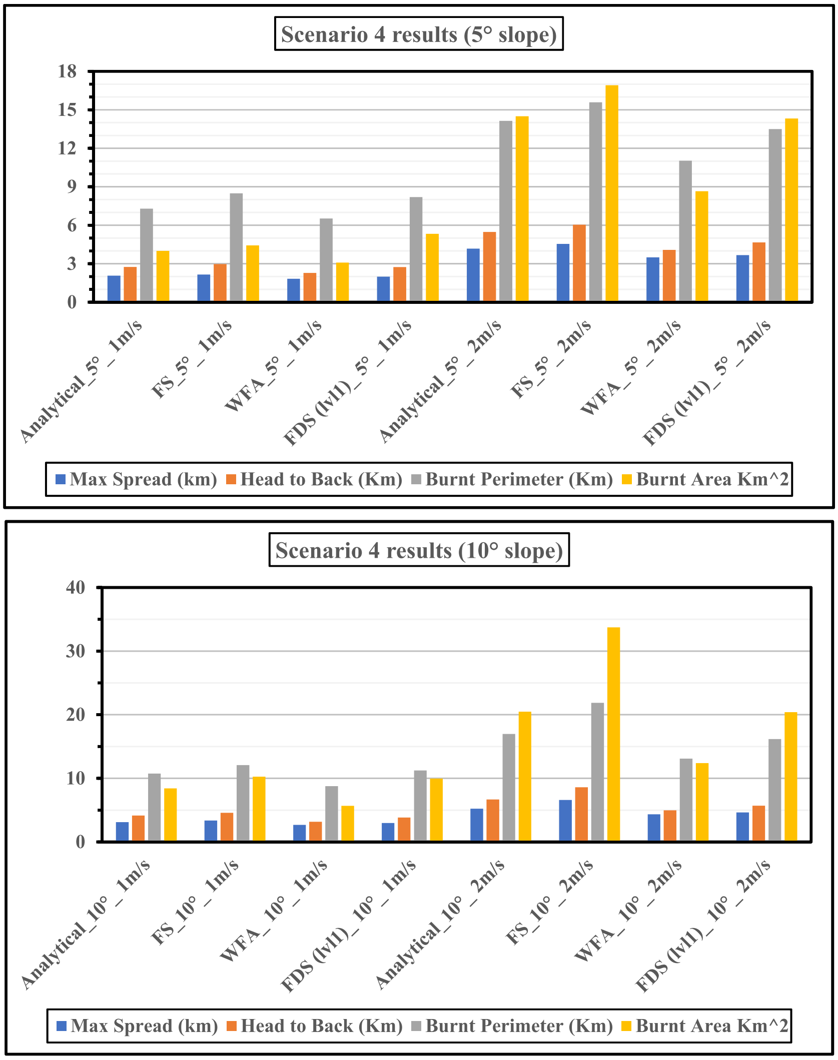

Fig. 4. Results and their variation of scenario 4 simulations.

purposes rather than operational decision-making, underscoring the trade-off between accuracy and computational efficiency. Even though all software platforms use the Rothermel surface spread model, significant variations were observed among their results. These differences arise due to several key factors, one of which is the simulation technique employed by each platform.

The first factor to consider is the underlying simulation approach. Wildfire Analyst and FireStation rely on cellular automation [55, 59], a method that divides the landscape into a grid where fire spread is calculated in discrete time steps based on localized conditions. In cellular automation, the landscape is divided into a grid of individual cells. The fire spreads from one cell to its neighboring cells in discrete steps, with the spread rate determined by local conditions such as wind speed, fuel type, and slope. Since the fire moves in grid-like patterns, the shape of the fire front tends to follow the grid's structure. This is why WFA and FS tend to produce fire fronts that appear more rectangular or blocky, as the spread is constrained by the underlying cell structure. In contrast, platforms like FDS (and FARSITE or BEHAVE) use an elliptical wave propagation method [65]. This method models fire spread as an elliptical front, where the rate of spread is calculated continuously in all directions, producing smoother and potentially more accurate simulations of fire behavior over complex terrains. In this method, the fire spreads outwards from a point in all directions, but at different rates depending on the influencing factors like wind and slope. This results in smoother, more natural curves in the fire front. The differing approaches between cellular automation and elliptical wave propagation contribute significantly to the variations in fire behavior predictions across these platforms, despite their shared reliance on the Rothermel model.

The second factor that needs to be considered is the fire shape model used by the different software. WFA and FS both rely on the Anderson [27,56] model, whereas FDS uses the Richards [66] model. These two models differ in how they conceptualize and simulate the shape and spread of fire, which contributes to variations in the results. Anderson's model is based on empirical data, where the dimensions of the fire ellipse are defined as proportions of the maximum fire spread relative to the wind speed at mid-flame height.

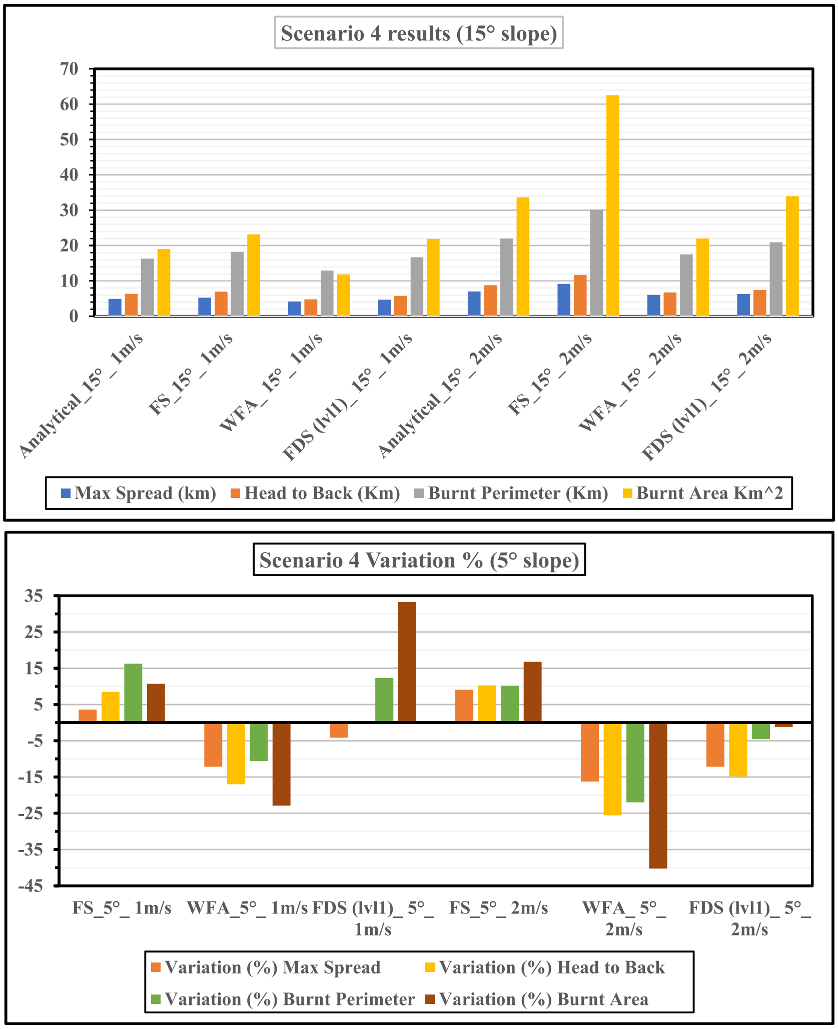

Fig. 4. (*continued*).

This provides a simplified but effective way to estimate fire growth in typical conditions. On the other hand, Richards' model uses the concept of wave propagation to create the fire shape. It treats each point along the fire front as a new ignition point for further propagation, allowing for a more sophisticated and dynamic fire behavior simulation. This approach accounts for continuous changes in environmental factors, making it more adaptable to complex fire scenarios.

To delve deeper into the differences in the implementation of the Anderson fire shape model, it's important to note that FS and WFA have taken distinct approaches. In FS, the fire shape is approximated using a 16-point method. Specifically, it selects 8 points at the head of the fire and 8 points at the back to approximate an elliptical shape [55]. This relatively straightforward method gives FS a consistent fire spread shape but can result in fire fronts that appear more angular or pointy, particularly at the head of the fire.

WFA enhances this approach by integrating both 8-direction and 16-direction models, while also introducing a novel 12-direction implementation. In this model, WFA selects 8 points at the head of the fire and 4 points at the back, where 4 of the head points are automatically chosen from the third ring of cells based on the wind direction, which drives the fire's greatest advance [59]. This gives WFA a more refined ability to model fire spread, particularly at the head, where the fire shape more closely follows the natural wind-driven propagation, but also makes the backing fire size smaller compared to other methods. As a result, the fire shapes in FS tend to be more pointed, while WFA produces a less pointy head and a shorter backing fire. These differences in fire shape models and the ellipse simplification methods are the reason that the fire shapes attained from software platforms differ as demonstrated, which correlates to the fire shapes produced by FS being the most pointy and rectangular, WFA rectangular but less pointy, and FDS with smooth curves. This can also explain the underestimation of the fire area from FS and WFA compared to the analytical solution and bigger areas from FDS, as the ellipse approximation leaves out some part of the ellipse area created from Anderson's model. In scenario 2 for instance, the burnt area obtained on 5° slope from WFA is the smallest (−11.6 %), followed by FS (−7.6 %) and then FDS (64.6 %), in which negative variation meaning the simulated areas are smaller than the analytical solution. In the following cases of 10° and 15° slopes, the burnt area obtained from WFA continues to be the smallest with the highest negative variation values (−31.71 % on 10° and

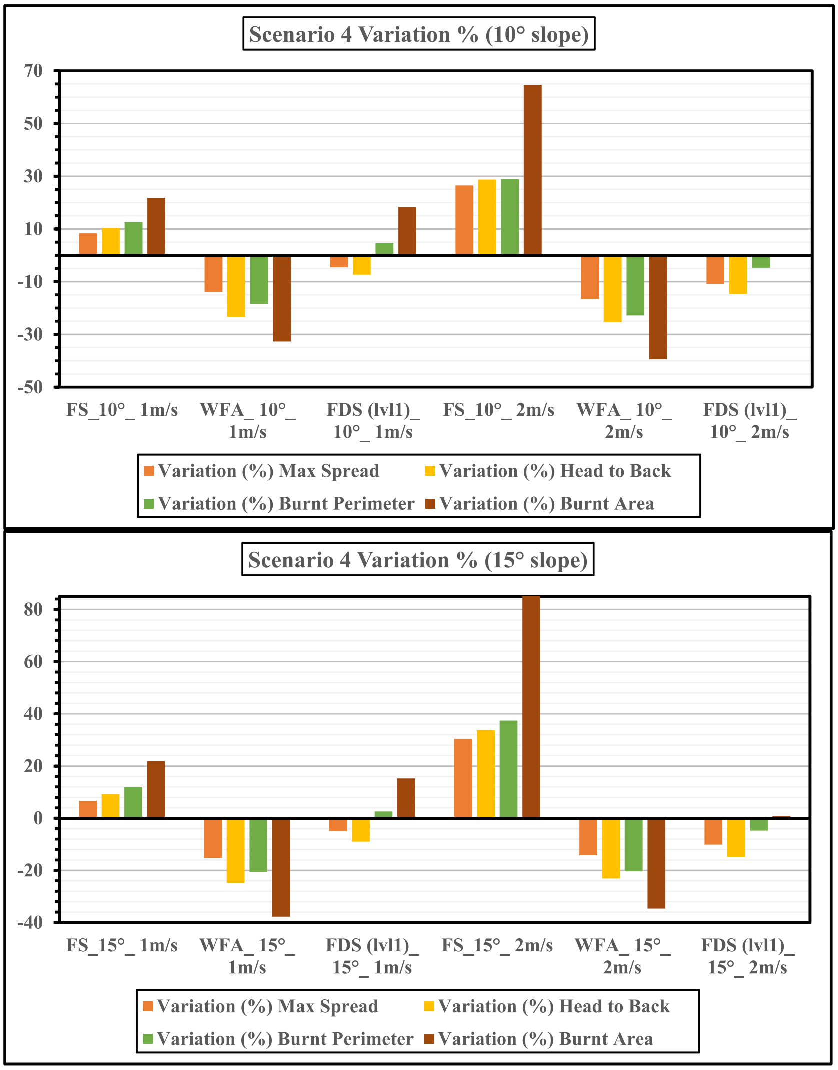

Fig. 4. (*continued*).

−44.64 % on 15° slope), due to the smaller backing fire size, followed by FS with smaller negative values due to ellipse approximation (−7.09 % on 10° and −15.20 % on 15° slope), and FDS with positive values which shows bigger burned areas (42.31 % on 10° and 25.64 % on 15° slope).

The FDS simulations presented in Figs. 6 and 7 seem to exhibit a more circular fire spread pattern compared to the analytical solution, suggesting that its fire shape model has a lower length-to-breadth ratio than the analytical solution. This implies that while the head-to-back distance in FDS may be similar to or even shorter than the analytical prediction, the lateral spread is greater. As a result, FDS often overestimates the total burned area, as the fire spreads more uniformly in all directions rather than forming the elongated elliptical shape typically anticipated in wildfire propagation models. This explains the significantly larger simulated fire area from FDS in contrast to the analytical solutions (see Fig. 8).

The third factor contributing to the variation in results among the three software platforms is the application of wind models. WFA employs the simplest approach, which interprets the provided wind characteristics—whether sourced from a forecasting organization or manually input—as representing wind speed at open ground, typically measured 20 feet (6.1 m) above the surface. WFA then applies the correction factor proposed by the Rothermel [19] model (0.4) to adjust this open-ground wind speed to the mid-flame height wind speed, which is used for solving surface fire spread.

FireStation, on the other hand, takes a more sophisticated approach. It reads wind inputs as points within the grid, typically simulating weather station readings that include wind speed, direction, and the height at which the reading was taken. It then offers two methods for solving the wind field across the grid: NUATMOS and CANYON, as explained in the software's chapter. After calculating the wind field, each point on the grid receives a unique wind vector, meaning that wind speed and direction vary across the landscape, accounting for local influences like terrain and topography.

Table 9
Scenario 4 simulation results.

Slope (degree)	Wind (m/s)	Software	Max Spread (m)	Head to Back (m)	Burnt Perimeter (m)	Burnt Area (ha)	Runtime (s)
5	1	Analytical	2074	2743	7298	399.7	–
		FS	2148	2976	8484	442.6	135
		WFA	1822	2277	6525	308.2	143
		FDS (lvl-1)	1988	2736	8197	532.7	1628
	2	Analytical	4171	5479	14,139	1449	–
		FS	4549	6043	15,580	1691.9	136
		WFA	3493	4080	11,032	865.7	135
		FDS (lvl-1)	3664	4666	13,498	1432	1674
10	1	Analytical	3114	4139	10,742	842.3	–
		FS	3374	4572	12,092	1025.9	230
		WFA	2679	3172	8765	566.8	174
		FDS (lvl-1)	2972	3836	11,243	997.2	3682
	2	Analytical	5211	6666	16,966	2048.4	–
		FS	6591	8581	21,862	3373.4	222
		WFA	4352	4972	13,099	1240.1	179
		FDS (lvl-1)	4646	5692	16,171	2039.6	6921
15	1	Analytical	4920	6360	16,278	1900.2	–
		FS	5250	6947	18,217	2316.1	363
		WFA	4173	4786	12,912	1184	190
		FDS (lvl-1)	4680	5788	16,695	2189.7	14887
	2	Analytical	7017	8758	21,979	3368.2	–
		FS	9156	11,709	30,204	6252.1	380
		WFA	6019	6735	17,509	2202.9	193
		FDS (lvl-1)	6309	7460	20,940	3394.8	22130

Table 10
Variation % of scenario 4 results.

Slope (degree)	Wind (m/s)	Software	Variation (%) Max Spread	Variation (%) Head to Back	Variation (%) Burnt Perimeter	Variation (%) Burnt Area	Variation (100 %) Runtime
5	1	FS	3.5	8.5	16.2	10.7	–
		WFA	−12.2	−17	−10.6	−22.9	0.05
		FDS (lvl-1)	−4.2	−0.2	12.3	33.3	11
	2	FS	9	10.3	10.2	16.7	–
		WFA	−16.3	−25.5	−22	−40.2	0
		FDS (lvl-1)	−12.1	−14.8	−4.5	−1.2	11
10	1	FS	8.4	10.4	12.6	21.8	–
		WFA	−13.9	−23.4	−18.4	−32.7	−0.24
		FDS (lvl-1)	−4.6	−7.3	4.7	18.4	15
	2	FS	26.5	28.7	28.8	64.7	–
		WFA	−16.5	−25.4	−22.8	−39.4	−0.19
		FDS (lvl-1)	−10.9	−14.6	−4.7	−0.4	30
15	1	FS	6.7	9.2	11.9	21.9	–
		WFA	−15.2	−24.7	−20.7	−37.7	−0.47
		FDS (lvl-1)	−4.9	−9	2.5	15.2	40
	2	FS	30.5	33.7	37.4	85.6	–
		WFA	−14.2	−23.1	−20.3	−34.6	−0.49
		FDS (lvl-1)	−10.1	−14.8	−4.7	0.8	57

FDS offers four different methods for applying wind, though only level sets 1 and 3 were used in this study. In level set 1, FDS creates a uniform wind field across the grid, similar to WFA, where the wind is applied uniformly without accounting for terrain effects on the wind field. In contrast, model 3 solves the Navier-Stokes equations over the grid, allowing it to incorporate the effects of terrain on wind behavior, resulting in varying wind vectors across the grid, similar to FS's method.

Thus, two main methods of wind application emerge among the software: a constant wind applied uniformly across the grid, used by WFA and FDS level set 1, and a more complex wind field calculation where unique wind vectors are applied to each grid point, used by FS and FDS level set 3. These differences in the wind models make direct comparisons of the results challenging. As shown in Scenario 3, FDS Level Set 3 produced the closest results for maximum fire spread, with a variation of 0.39 % for a 1 m/s wind and −11.20 % for a 2 m/s wind, followed by FDS Level Set 1, which showed a variation of −5.15 % for 1 m/s and −12.62 % for 2 m/s. WFA

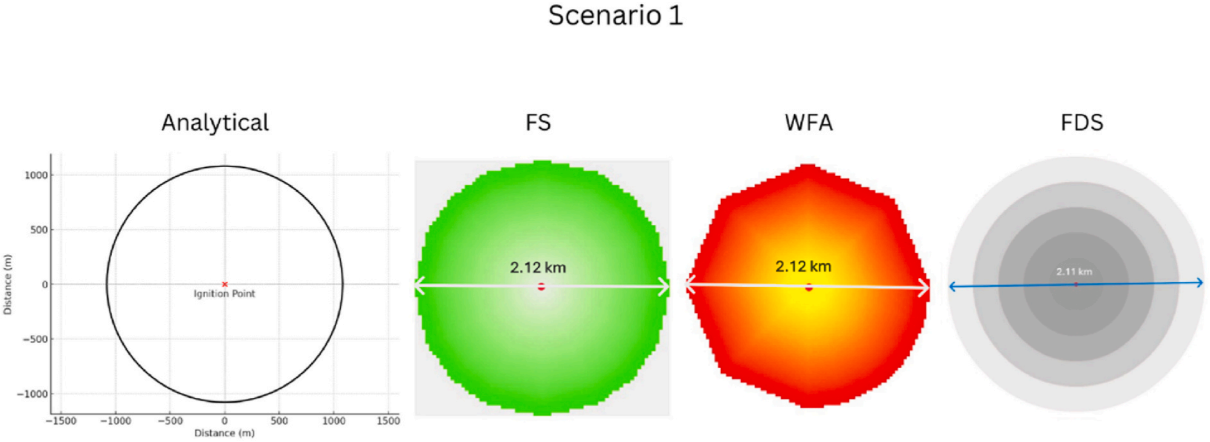

Fig. 5. Fire shapes scenario 1.

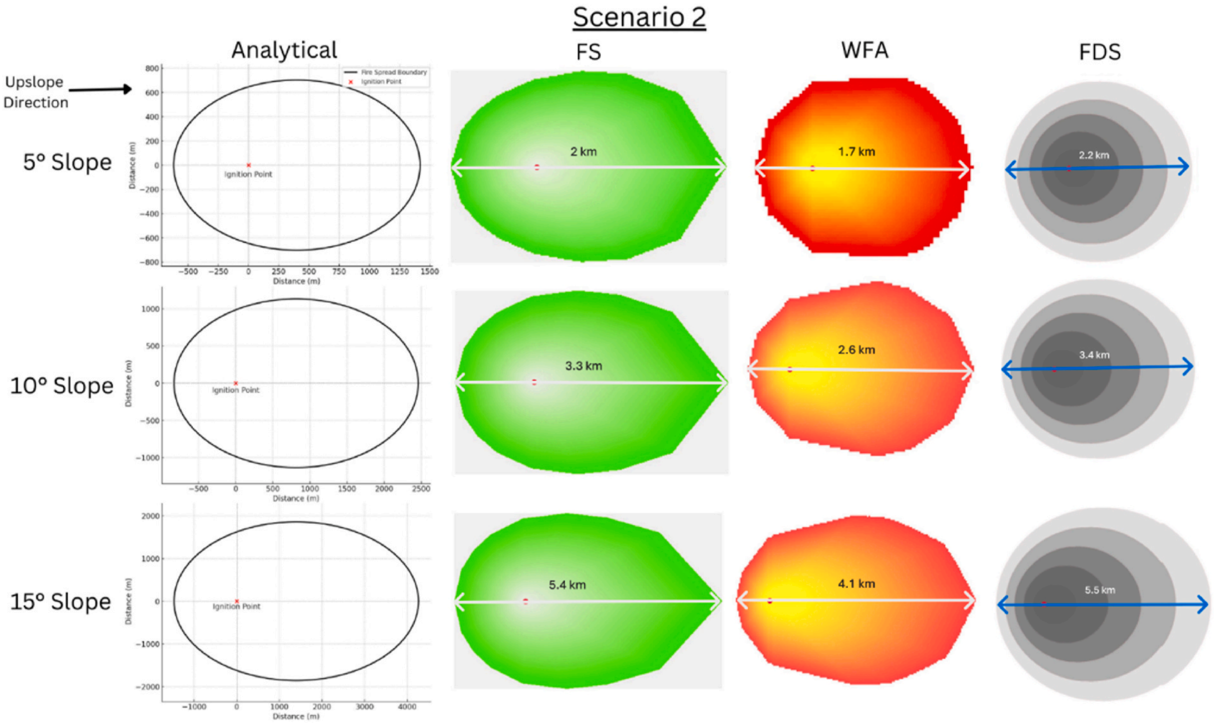

Fig. 6. Fire shapes scenario 2.

came in third, with a difference of −7.86 % for 1 m/s and −14.57 % for 2 m/s, while FireStation (FS) had the largest variation at −9.62 % for 1 m/s and −17.50 % for 2 m/s wind. However, when comparing the burnt area based on the final fire shapes simulated by each platform, the trend follows that of scenario 2. WFA resulted in the smallest area variation from the analytical solution, with −20.07 % for 1 m/s and −42.33 % for 2 m/s wind. FS followed closely, showing a variation of −20.47 % for 1 m/s and −33.05 % for 2 m/s. FDS Level Set 1, in contrast, produced much larger area variations, with 33.56 % for 1 m/s and 3.34 % for 2 m/s wind. Finally, FDS Level Set 3 had the largest area variation, with 45.73 % for 1 m/s and 6.28 % for 2 m/s wind. These discrepancies highlight how differences in wind modeling among the software significantly impact both the fire spread and burnt area predictions.

When the results for Scenario 4 from FDS using Level Set 3 were obtained, significant differences in the simulation of the fire front and fire shape were observed, as demonstrated in Fig. 9. Due to the drastic deviations from expected behavior, these results were removed from the study to maintain the integrity of the comparison. Upon investigating the cause of the issue, it was found that the wind field developed unusual behavior over the terrain in the lateral direction, leading to inaccuracies in fire spread modeling.

FDS employs rectangular mesh grids, representing geometry with structured Cartesian grids. This method approximates the terrain

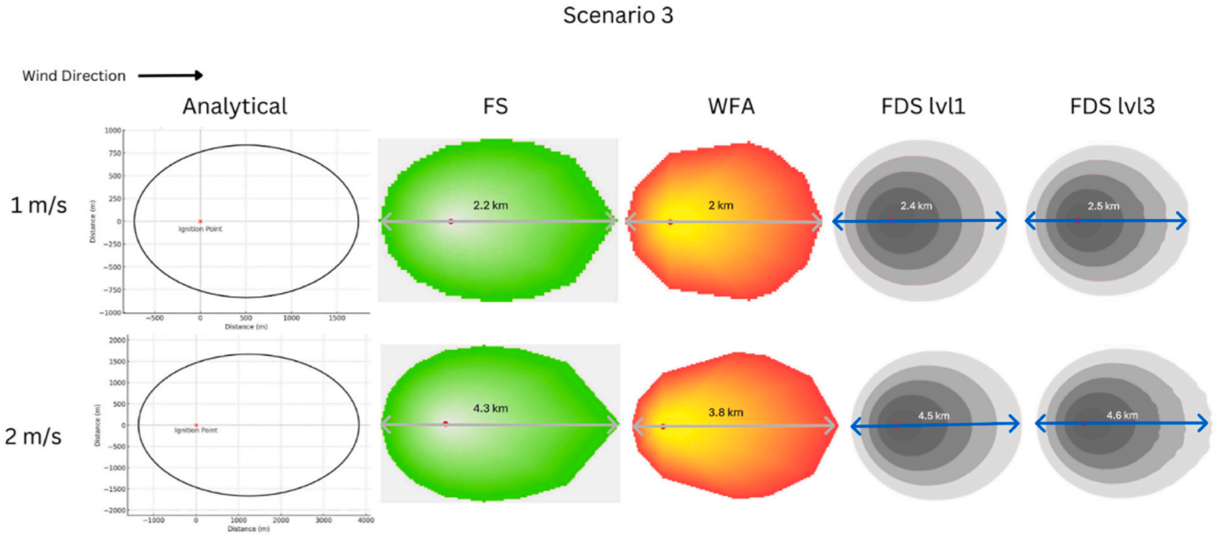

Fig. 7. Fire shapes scenario 3.

using stacked horizontal layers, where each elevation change is limited by the set grid resolution. The text command for the simulation was prepared using the “qgis2fds” add-in from the QGIS software, which converts terrain into discrete elevation blocks. The size of these steps depends on the cell size of the input data, which in this study was set to 25 m—consistent with the available data for fuel maps and elevation models. For consistency, the mesh size across all platforms was also set to 25 m. However, when FDS simulates Scenario 4 using Level Set 3, which incorporates the interaction between the wind field and the terrain, these simplified steps on the sloped ground introduced problems. Specifically, the stepped representation of the terrain created circulations that moved laterally to the wind direction, causing wind vectors to increase in the lateral direction rather than flowing predominantly upslope. As a result, the fire spread more laterally than upslope, shifting the head of the fire to the direction perpendicular to the slope. This abnormal fire behavior significantly altered the fire shape and front, leading to unreliable results.

This outcome from the FDS simulation could be a subject for further investigation. The interaction between wind and terrain, particularly when terrain is simplified into steps that are the same size as the simulation mesh, raises important questions. The “step effect,” where simplified terrain creates wind circulations, may influence fire behavior in ways that require deeper exploration, especially when the grid resolution is coarse enough to rough out the terrain details.

The effects of each sub-model or method used in different software platforms can significantly influence the outcomes of specific simulations, and this is an essential consideration for any practitioner working with such tools. First and foremost, practitioners should be throughly familiar with the specific tool they are using, including its sub-models and methods. A solid understanding of these components can help reduce errors or biases that may impact real-life operations.

Second, it is crucial for users to understand the range of effects these sub-models can have on the results. This knowledge allows for better judgment and more effective decision-making in wildfire management or simulation tasks. This study demonstrated the impact of different sub-models and methods incorporated in three software platforms, all of which use the same surface propagation model. A user not fully aware of these subtle differences might assume that the tools will produce the same results with identical inputs, but this study showed that this is not the case.

However, this research has its limitations due to insufficient resources and time constraints, and there remain many topics within this scope that could be explored in future studies. The effects of adjacent fuels, different wind directions relative to slope, variations in fuel moisture content, and the sensitivity of each factor on the final result could all be interesting subjects for further investigation in this field.

6. Conclusion

This study compared the effects of varying wind and slope conditions on three wildfire simulation software platforms—Wildfire Analyst, FireStation, and Fire Dynamic Simulator—all of which use the same surface fire propagation model (Rothermel) as their foundation. The primary objective was to clarify how the different sub-models or methods incorporated into each software might influence the simulation outcomes. The findings from our comparison analysis revealed considerable differences in simulating identical scenarios using these tools. These findings highlight the need to consider numerous critical elements in wildfire simulations, in addition to the software’s well-established qualifications.

Four simple scenarios were designed as test cases, which were simulated using each platform with identical inputs across all platforms. Additionally, the scenarios were solved analytically using the Rothermel model and Anderson model equations to provide a reference point for comparison. The simulation results demonstrated that each platform produced a range of outcomes, showing

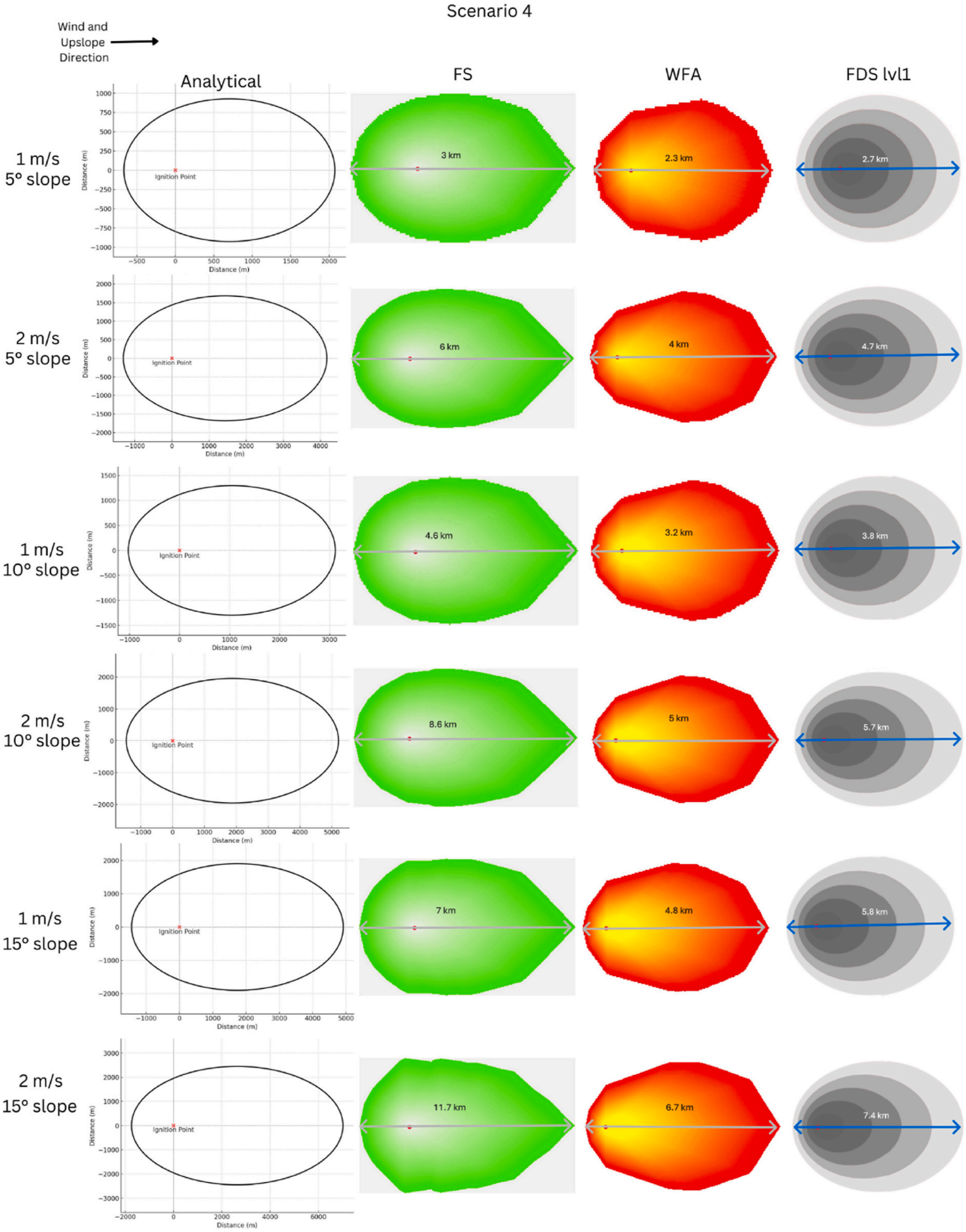

Fig. 8. Fire shapes scenario 4.

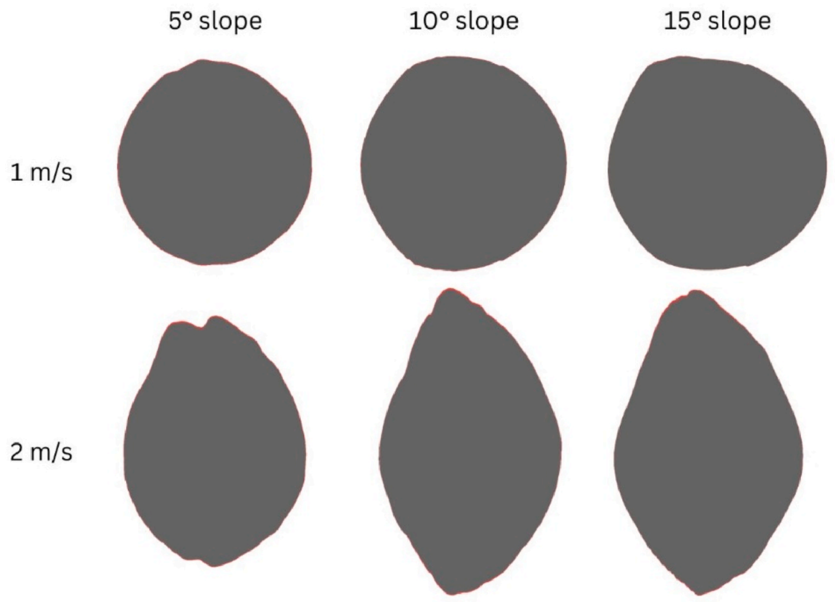

Fig. 9. Fire shapes of FDS level set 3 for scenario 4.

variations from both the analytical solution and among themselves.

Various uncertainties are associated with predicting fire behavior factors, such as maximum spread rate, head-to-back fire spread, final burnt area, and burnt perimeter, as assessed in this study. These uncertainties stem from multiple factors, including variability in fire shape models, wind field calculations, and simulation techniques, which introduce differences in fire spread and burnt area estimations. The resolution of input data, such as digital elevation models and fuel maps, also influences accuracy, particularly when terrain is represented using discrete steps, as observed in the FDS simulations. Additionally, the numerical methods employed across different software platforms, such as grid-based cellular automata versus elliptical wave propagation, significantly impact fire propagation patterns.

The study revealed that the effects of each sub-model or method differ in how they influence the simulation results. Among these, the simulation technique (cellular automation versus wave propagation) had the least impact on the results, with this effect diminishing further as the simulated fire size increased. The fire shape model, however, proved to be a significant factor in determining the final burnt area. The Richards model consistently produced larger burnt areas compared to the Anderson model, and the ellipse approximation method also impacted the fire's final shape. The application of wind models combined with the slope effect appeared to have the greatest influence on the variation of results across platforms.

The observed variances demonstrate the complex character of fire behavior simulations, in which outcomes can be impacted by the case's inherent complexity, the accuracy of input data, the intended application of simulation results, and the software operator's expertise. Therefore, users or practitioners must have a comprehensive understanding of the tools they are using, including the different sub-models and methods integrated within them. This knowledge is essential for assessing the effects on results and is critical for informed decision-making and operational effectiveness.

CRediT authorship contribution statement

Shahab Mohammad Beyki: Writing – original draft, Visualization, Validation, Methodology, Investigation, Conceptualization. **António Gameiro Lopes:** Writing – review & editing, Supervision, Software. **Luís Laím:** Writing – review & editing, Supervision. **Aldina Santiago:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Shahab Mohammad Beyki reports financial support was provided by Foundation for Science and Technology. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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