Finanziato dall'Unione europea
NextGenerationEU

D 3.1 Web-gis application comprising the modeling tools

Work Package: WP3

Work Package leader: CNR-IBE
Deliverable leader: CNR-IBE

FIREBOX
Innovative Tools for Wildfire Prevention

NATIONAL RECOVERY AND RESILIENCE PLAN (NRRP) – MISSION 4

COMPONENT 2 INVESTMENT 1.1 – "Fund for the National Research Program and for Projects of National Interest (NRP)"

Project code: P2022MXRK9

CITATION:

Casula M., Ventura A., Arca B. (2026). D3.1 Web-gis application comprising the modeling tools. National Recovery And Resilience Plan (NRRP) – Mission 4, Component 2 Investment 1.1 – Fund for the National Research Program and for Projects of National Interest (NRP)”, Project FIRE-BOX – Essential tools for wildland fire risk management in Italy.

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Executive summary

This document describes the architecture and operational capabilities of the wildfire spread simulator developed by CNR IBE within the FIRE-BOX project. The simulator is designed to support public institutions and fire management agencies in planning tactical and strategic wildfire prevention and suppression operations, providing accurate and computationally efficient predictions of fire front evolution in real time or off-line.

The modelling chain integrates three core components: a data management module, a mass-consistent wind downscaling model operating at 30 m resolution, and a fire front propagation module combining the Rothermel semi-empirical fire behavior model with the Level Set method for spatial front propagation. Input data include static morphological layers — topography, vegetation type, forest cover and fuel models — and dynamic meteorological data sourced from local observations or numerical weather models. The fuel models adopted follow the Anderson (1982) and Scott and Burgan (2005) standards, complemented by additional models defined for Mediterranean vegetation types.

The simulator produces maps of rate of spread, fireline intensity, flame length and time of arrival, which are key parameters for assessing fire severity, defining suppression strategies and evaluating operational safety. The system has been validated against a set of real fire events that occurred in Sardinia, demonstrating substantial agreement between simulated and observed fire perimeters at a computational cost compatible with real-time applications.

The simulator also computes fire propagability, defined as the probability that a given point in the territory will be reached by fire within one hour, pre-calculated for 144 meteorological scenarios combining three wind intensity levels, 16 wind directions and three fuel moisture conditions. These maps provide operators and park managers with a near-real-time risk assessment tool for both forecasting and strategic planning purposes.

Keywords

Wildfire spread simulation; Rothermel fire behavior model; wind downscaling; fire propagability; real-time fire forecasting, Level Set method

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1. Introduction

Wildfire risk is increasing across the Mediterranean basin and in Italy in particular, driven by climate change, land abandonment and the expansion of wildland-urban interface areas. In this context, the availability of operational tools capable of providing accurate and timely predictions of fire spread behavior is a critical requirement for public institutions engaged in wildfire prevention, risk assessment and emergency response. The operational application of fire simulators enables rapid determination of the probability and severity of fire events based on the combined effect of weather conditions, terrain morphology and vegetation fuel characteristics, supporting both tactical decisions during active fire events and strategic planning for prevention and preparedness.

This document describes the wildfire spread simulator developed by CNR IBE within the FIRE-BOX project, presenting its software architecture, the structure of the modelling chain and the simulation outputs, with reference to validation results obtained on real fire events that occurred in Sardinia. The simulator constitutes the core component of the modelling tools released under Milestone 8 of the project, and its operational use is documented in the companion Deliverable D3.2 – User guide of the modeling tools, which provides detailed instructions for accessing the web-GIS interface and running both deterministic and probabilistic simulations across the National Park domains.

The simulator relies on a set of input layers produced within other work packages of the FIRE-BOX project. The fuel type maps and associated fuel properties were developed within WP1 FUEL BOX, specifically through Deliverable D1.2 (Fuel Type Map at the national scale), and subsequently used to assign fuel models according to the methodology described in Deliverable D1.3 (Fuel model map parameterized for Rothermel-based modeling applications). Together, these inputs constitute the complete dataset required to characterize fire behavior across the simulation domains established for each Italian National Park considered within the project.

2. Objective

The development of the wildfire spread simulator pursued a set of scientific and operational objectives aimed at providing Italian fire management institutions with a modern, accessible and physically grounded tool for wildfire risk assessment and emergency support.

The primary objective was to develop a modelling chain capable of predicting the spatial and temporal evolution of a wildfire front with sufficient accuracy and at a computational cost compatible with real-time operational requirements. This required combining a physically based fire behavior model with an efficient front propagation algorithm and a wind downscaling procedure capable of accounting for the complex orography of the Italian National Park territories.

A second objective was to make the tool accessible to a broad range of institutional users — including park managers, forest services and civil protection agencies — without requiring specialized modelling expertise, through the development of a web-GIS interface operable from any network-connected device.

A third objective was to extend the simulator's capabilities beyond the simulation of individual fire events, enabling the probabilistic characterization of fire hazard across entire park territories through the pre-computation of propagability maps for a comprehensive set of meteorological scenarios. This functionality is intended to support not only real-time operational decisions but also long-term strategic planning, prevention zoning and firefighting resource allocation.

More broadly, the simulator was conceived as a tool to improve the effectiveness and safety of suppression operations, by providing quantitative estimates of fireline intensity and rate of spread that allow operators to assess intervention feasibility and identify areas where aerial or ground-based operations can be conducted safely and effectively.

3. Simulator description

The simulator uses a series of inputs, some of which are necessary to characterize the individual event, while others are available to the system for multiple fires, such as morphology and weather conditions, that characterize a larger region in which it is desired to simulate a fire. The location and time of ignition, duration of the fire, and size of the simulation domain are part of the first group, while weather conditions, orography, fuel type, forest cover, and surface roughness can be grouped into a second group. This second group can be further broken down into static data relating to morphology and dynamic data related to meteorologic conditions that is updated hourly.

3.1 Static data: Morphology

Morphological data are considered to be static, as they vary over much longer time scales respect to meteorological data.

Morphological data have a resolution of 10m. The system, working at higher resolutions (100 m-30 m), therefore extracts data considering the average value for orography, vegetation height, and forest cover, while for data related to land use, such as fuel type, the most frequent value falling within the single cell into which the simulation domain is divided is considered.

The fuel models adopted are the Anderson (1982) and Scott and Burgan (2005) standards and a set of other models defined for grasslands, agricultural crops, and Mediterranean scrub. The models provide for a different load for the living and dead fractions, the latter being divided into three categories according to thickness: less than 0.6 cm, between 0.6 cm and 2.5 cm, and greater than 2.5 cm. Each fuel model is characterized by surface-to-volume ratio, fuel height, and extinction moisture content beyond which the fire cannot spread. The map of land use and fuel model used in the simulations are the part of the Firebox work developed in WPXXX.

3.2 Dynamic data: Meteorology

The meteorological data used to initialize the system can come from either local observations or a weather model. Although the system supports direct interfacing with the WRF (Weather Research and Forecasting) meteorological limited area model, this aspect is not covered by the Firebox project. However, the WRF model was used to validate the flame front simulations: set to the specific requirements of fire simulation, minimizing the error on wind fields by comparing the simulated data with observations from the official Arpas control units distributed throughout the Sardinia region, it was used to produce weather data for the 2019-2020-2021 fire season in order to test the simulator's performance in the past years. As in the case of morphological data, meteorological data also requires the adaptation of wind fields to an orography described with a resolution of the order of tens of meters. Extension of the validity of Meteorological data originating from measurements or local point estimates could be considered representative for a wider domain only if the domain could be considered homogeneous, that is at least in the absence of orographic obstacles. But in reality things are different, so orographic obstacles must be taken into account. A technique has therefore been developed by which, starting from an initial point estimate, generates a wind field that takes into account the complexity of the orography.

The same problem arises when initializing the simulator from a meteo model, whose resolution cannot be the tens of meters needed to simulate fire propagation. At the same way even in this case an important error is introduced: when switching to a higher resolution orography, the topography is substantially different, i.e., obstacles to the flow not present before are introduced or, conversely, free spaces that were not visible at lower resolutions are created. From a physical point of view, this therefore leads to a violation of the principles of conservation of momentum, energy, and mass.

3.3 Wind downscaling model

In order to take int o account local fluid dynamic effects due to complex morphology, the mass-consistent model is dedicated to downscaling to a resolution of 30 m the wind fields provided by a meteorological model or by observations. The downscaling approach is based on relaxing the constraints derived from the general principles of conservation of mass, energy, and momentum. This last conservation law, which involves three scalar equations as it is a vector quantity, entails a computational load that is not compatible with real-time requirements. Energy and mass, on the other hand, are scalar quantities and therefore the principle of their conservation leads to scalar equations. Of the five equations that deal with the complete physics, in our simplified approach, we will only consider the principle of mass conservation. The basic idea is to adjust an initial wind field hypothesis so that the mass continuity equation is respected. Therefore, considering all possible non-divergent vector fields, will be selected the one closest to the initial hypothesis based on meteorological simulations or local measurements. The implementation of the method leads to a variational problem, first proposed by Sasaki in 1958, which is solved by a generalization of Lagrange multipliers for the Hilbert space of square-integrable functions. To simplify the problem, the approximation of air incompressibility (where air density is considered constant) is introduced, allowing two differential equations to be obtained: a second-order elliptic equation, dependent only on the initial field, and a second first-order equation. The solution strategy involves a numerical finite difference approach with a regular horizontal grid, while, to provide a better representation of the lower part of the planetary boundary layer, the distribution of the 128 vertical levels follows an exponential law, with the first level set at 1.3 m. The second-order equation is solved first using Jacoby's iterative method, while a direct solution is used for the first-order equation, which is solved subsequently. The maximum height of the domain depends on the orography and is set at 3500 m above the highest point of the domain. If the equations were solved in Cartesian coordinates, complex topography could induce large velocity errors near the surface (Ross et al. 1988): therefore, a “terrain following” coordinate transformation is introduced. A multigrid technique and parallel code execution were used to speed up convergence.

3.4 The Flame Front Propagator

The simulator is based on the implementation of Rothermel's quasi-empirical model equations to characterize the local fire behavior depending on wind, fuel humidity and slope, and on the Level Set method to simulate the fire propagation. Rothermel's fire behavior model (Rothermel 1972) was chosen because it offers a good compromise between accuracy, computational effort, and therefore agility in operational applications. The model predicts fire behavior using equations that consider the energy generated by the fire, the heat transferred from the fire to the adjacent plant fuel, and the energy absorbed by the fuel itself. Its formulation is based on a series of laboratory experiments conducted using small, homogeneous dead fuels. The characteristics of fire behavior, in particular the propagation speed and intensity of the fire line, are calculated using quasi-empirical functions of a large number of independent variables that affect propagation. Fuel properties are provided separately for live and dead components and for different size classes. Mean values of the properties between size classes are calculated using the surface area/volume ratio as a weighting factor, while the living and dead fractions are treated separately. As regards the fire propagation technique, the level-set approach was chosen with the aim of providing a tool more suited to operational applications, as it is characterized by greater computational agility and better portability to parallel computation than vector simulators. The level-set method uses a Hamilton–Jacobi equation (a hyperbolic partial differential equation) to describe the propagation of the fire front, which is defined implicitly in a two-dimensional flat space. The simulator has been tested and evaluated on a set of fires that have actually occurred in Sardinia in recent years. The set includes medium and large fires chosen to reflect the average behavior of fires historically observed on the island. The selected fires were characterized by an active propagation phase of less than 10 hours. The most of the case studies involved fires that occurred with wind speeds ranging from breezes to strong winds (2–15 m/s). In terms of vegetation type, the areas affected by the fires were characterized by herbaceous and shrubby vegetation, typically Mediterranean and in particular low scrub characterized by a moderate or high fuel load, as reported by the authors in previous studies conducted in Sardinia (Arca et al. 2007; Salis et al. 2016a; Salis et al. 2016b).

The simulator is able of providing a series of useful outputs for characterizing fire behavior. The rate of spread, estimated in meters per minute, is an essential parameter for setting up firefighting activities and also for identifying areas particularly at risk, such as the outskirts of inhabited areas, which, thanks to the estimation of the propagation speed and the time of arrival of the flames, can be adequately protected, for example with civil protection measures. Another essential factor for planning firefighting operations is fireline intensity, which estimates in W/m2 the energy released by plant fuel per meter of fire front; this parameter is essential because allows the thresholds necessary for safe extinguishing operations to be set and, therefore, the areas of the territory most suitable for safe operations to be identified. The same applies to aerial interventions, which, above a certain fireline intensity threshold risk being completely ineffective. The system has also the possibility to simulate a fire barrier in order to consider different firefight strategies or to simulate a land use change in order to limit the fire prone condition of a territory.

Below is a series of maps relating to the Orrì case study (July 13, 2019), during which the flames affected an area with tourist infrastructure, necessitating the evacuation of the facilities and beaches. The simulator provided very useful input data for reconstructing how the event unfolded and for simulating the firefighting operations. Furthermore, during the validation of the simulator outputs, we verified that the progress times predicted by the simulator were fairly consistent with what actually happened in the field. The values of the flame front intensity are also in line with the estimates made by the CFVA personnel who intervened during the extinguishing operations.

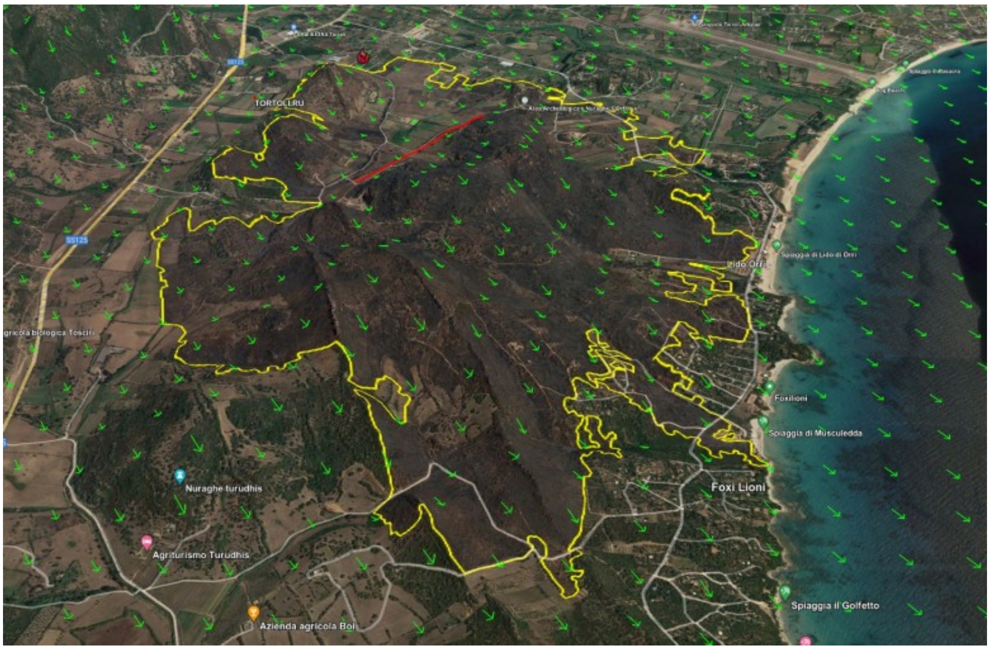

Figure 1: Wind field predicted by the meteorological model chain for the case study of Orrì (13/07/2019).

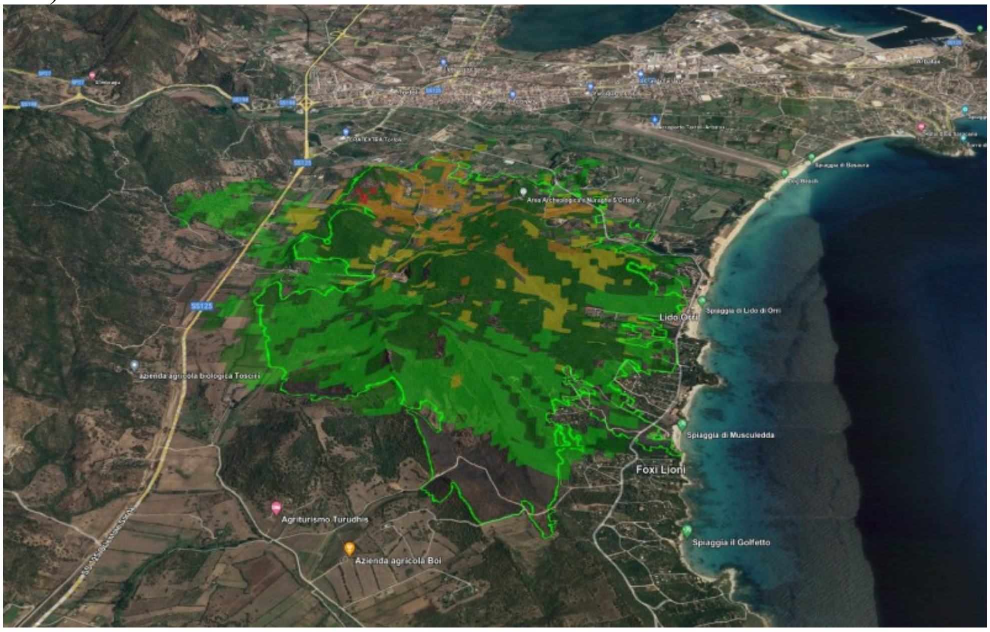

Figura 2: Map of the propagation speed of the Orrì case study (July 13, 2019); the orange and red areas are characterized by propagation speeds exceeding 25 meters per minute.

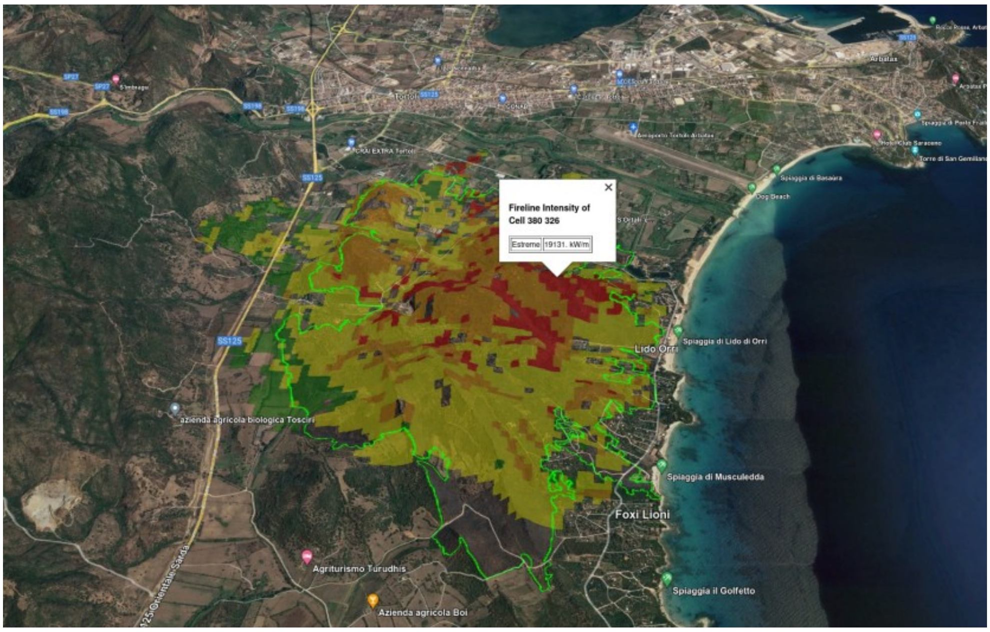

Figura 3: Map of flame front intensity for the Orrì case study (July 13, 2019); the red areas are characterized by intensities greater than 19,000 kW per meter.

3.5 Propagability and short term fire probability

Considering the active fire fighting strategies, since it is impossible to know in advance the path of a fire that may be triggered in the future, are useful probabilistic estimates of the likelihood of those events and how they will behave. Probability is defined as the number of favorable events compared to possible events. If we want to describe the probability that a given point will be affected by fire within the next hour, we must consider the number of times that the point (representative of its surroundings of 100m x 100m, which we will now call a pixel) is burned compared to the number of fire events that could reach that point. It is important to emphasize how crucial is to define all the fires that "could reach that point," as this represents the denominator of the fraction and an incorrect calculation would significantly alter the result of the estimate: considering a point A, a fire starting 20 km away from it clearly has no physical possibility of reaching that point in an hour, even in extreme conditions, and therefore clearly must be excluded. Extreme conditions of propagation can be represented by a front that spreads for hours at an average speed of 1.5 m/s or more, i.e., 5.4 km/h. Considering this value as maximum speed, we can assume that in one hour a fire will reach 5.4 km from the ignition point. The probability of a fire occurring in the next hour will then be equal to the fraction of fires started within circle of radius of 5.4 km which reach circle center. In other words, the probability is equal to the ratio between the number of fires that reached that point and the number of fires that started in an appropriate area around that point.

The SWS fire simulator is able to simulate the evolution of the flame front of a single event based on morphology and meteorology. To describe how each point in the entire area of interest would behave if it were traversed by fire originating from different ignition points, we assumed that the entire domain is "seeded" with a series of ignition arranged on a regular grid with a 100m mesh. Each fire was simulated with a duration of one hour at a spatial resolution of 100m. We then considered all the times that each pixel was burned and divided this number by the number of fires triggered on a circle with a radius of 5.4 km centered on the considered point: the ratio is the average probability (possibly expressed as a percentage) that if a fire is triggered within a radius of 5.4 km from a point, that point will be burned in the following hour. In other words, it is the average percentage of fires that start at any point within a 5.4 km radius of the point in question and reach that point within an hour. We can call this spatialized information relating to the territory **fire propagability**, and it is a characteristic determined by weather conditions and the morphology of the territory.

We emphasize that the possibility that a part of the territory may actually burn depends not only on the speed with which the fire fronts spread towards a given point, but also on the number of ignitions located in the neighboring region. A central element in estimating the probability of fire is therefore the probability of ignition, without ignitions there would be no fire. Given that in mid-latitude regions the non-anthropogenic contribution to the genesis of ignition points is completely negligible, the historical probability can be used to consider the probability of ignition. Therefore, a simple product of this latter estimate and the percentage of fires that reach a point provides the probability that this point will be burned if those specific weather conditions occur on that day of the year at that time. To provide an estimate that could take into account all the most frequent weather conditions based on different wind intensity and direction values and various fuel moisture values, we calculated the propagability for three wind intensity conditions: 2.5 m/s, 7.5 m/s, and 12.5 m/s, representing low, medium, and high wind conditions, for 16 directions arranged at regular angular intervals of 22.5° and for three humidity conditions, high, medium, and low, thus obtaining 144 maps that can be selected depending on weather conditions. In order to provide a useful risk estimate for tactical and strategic activities, it is necessary to obtain the estimate in advance respect the fire event. A system of automatic map selection has therefore been devised in order to determine which weather scenario is most representative for a given weather condition. Considering that, in general, weather conditions can vary considerably from one point to another within a region, it is not possible to select a single scenario that is suitable everywhere. It will therefore be left to the operator to select the most appropriate climate scenario representing the actual weather conditions.

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