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Numerical study of high intensity experimental field fires across Corsican shrubland vegetation

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Abstract

Field-scale experiments have been conducted on steep sloped terrains in Speluncatu and Letia, north-western and southern regions of Corsica. This work lies within the GOLIAT project framework and it was provided by the Fire and Rescue Service of North Corsica and the Corsican DFCI (Défense de la Forêt Contre l'Incendie) Group. This work reported high intensity fires propagating through shrub vegetation areas (*Genista Salzmannii*) lying between 60 cm and 85 cm. These sites were selected because of the density of the vegetation, the high slope angle values with a wind direction aligned with the main slope, which can generate a fire close to wildfire behaviour. A detailed experimental protocol is used in order to determine the propagation conditions and the fire behaviour using UAV cameras and heat flux gauges. In order to investigate the different phenomena encountered in these types of fires, numerical simulations were conducted using a complete physical fire model, based on multiphase formulation, namely FireStar2D. Numerical predictions were used to examine the fire front dynamics related to the fire's rate of spread and fireline intensity. Despite the unfavourable wind and humidity conditions, experimental results analysis showed that the fireline intensity was higher than 7 MW/m, which means that these fires fall into the category of the very high fire severity. Numerical results predicting the fire's rate of spread, fireline intensity and fire impact were in good agreement with the experimental data.

1. Introduction

Wildfires represent one of the main causes of the natural capital damage in the regions characterized by the Mediterranean climate like the Mediterranean basin, Chile, California, South Africa, and South and South-West of Australia. The Mediterranean climate is characterized by a high seasonality that can be summarized as hot, dry summers, and mild wet winters (di Castri 1981). Changes in climatic and weather conditions in these regions are one of the major reasons for the increase in wildfire risk, where they tend to be warmer and drier with more frequent heat waves (Benson et al. 2008; Sommers et al. 2011). Thus, in the presence of flammable vegetation, these climate conditions are prone to fire ignition and propagation. The real problem is that the Mediterranean region is witnessing a new wildfire context characterized by high intensity dangerous fires that present a real threat where their behaviour is unpredictable and uncontrollable.

In general, extreme fires are characterized by a high fireline intensity, and a high rate of spread, with the possibility of spotting or suddenly changing the fire behaviour (Alexander 1982). Firefighters know that beyond a threshold of 10 000 kW/m, a fire becomes erratic and incontrollable (Tedim et al. 2018). Indeed, fireline intensity has become one of the standard criteria by which firefighters estimate the difficulty of controlling a wildfire, and also the most appropriate descriptor of immediate fire effect on vegetation. The real problem is that extreme wildfire events tend to overwhelm suppression efforts, and cause lots of humans and economical

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losses (Tedim et al. 2018; European Science & Technology Advisory Group 2020). This new context requires adapted policies to shift the focus from suppression to prevention that requires a good knowledge of the physical mechanisms governing fire behaviour like ignition, fire spread and fire impact. Many experimental fires have been conducted at the field scale (Cheney et al. 1993; Cheney and Gould 1995; Marsden-Smedley and Catchpole 1995; Vega et al. 1998; Viegas et al. 2002; Morandini et al. 2006; Mueller et al. 2018), but there are only few data for high intensity fires. Therefore, relevant experimental data on high-intensity wildfires is of paramount interest and experiments at the field-scale are highly valuable. Such fires are often subject to the vagaries of the weather and variations in the vegetation and land topography (Mulvaney et al. 2016). The interaction of these, and even with the fire itself, can result in seemingly capricious behaviour.

In this context the main purpose of this work is to present experimental data of the fires carried out at large scale fields, having important slopes, resulting in high fire intensities. This field-scale experiments have been conducted in two different regions of Corsica in March 2021 and 2022 and October 2021. In order to understand and investigate the different phenomena encountered in this type of fires, the experimental results are compared to the prediction provided by a complete physical model, namely FireStar2D (Morvan et al. 2009). In the next section the experimental method is described, followed by the modelling approach that was used. Finally, an analysis and a discussion of the relevance and the significance of the results are presented.

2. Experimental method

2.1. Site description and experimental protocol

Experimental sites were selected because of the structural homogeneity of the *Genista Salzmanni* vegetation with a coverage > 90%, and also because of the steep slopes that can generate high intensity fires. Slope values are obtained by measuring the coordinates of four poles positions as shown in Figure 1, using *a high-precision Global Navigation Satellite System (GNSS).* Concerning the experimental protocol, measuring devices were deployed in the field: Heat flux sensors and thermocouples were placed in the vegetation free area, video cameras were located on the sides of the plot, wind properties and ambient conditions were recorded using a weather station and fire propagation was recorded from above using a drone-mounted Visible-IR camera.

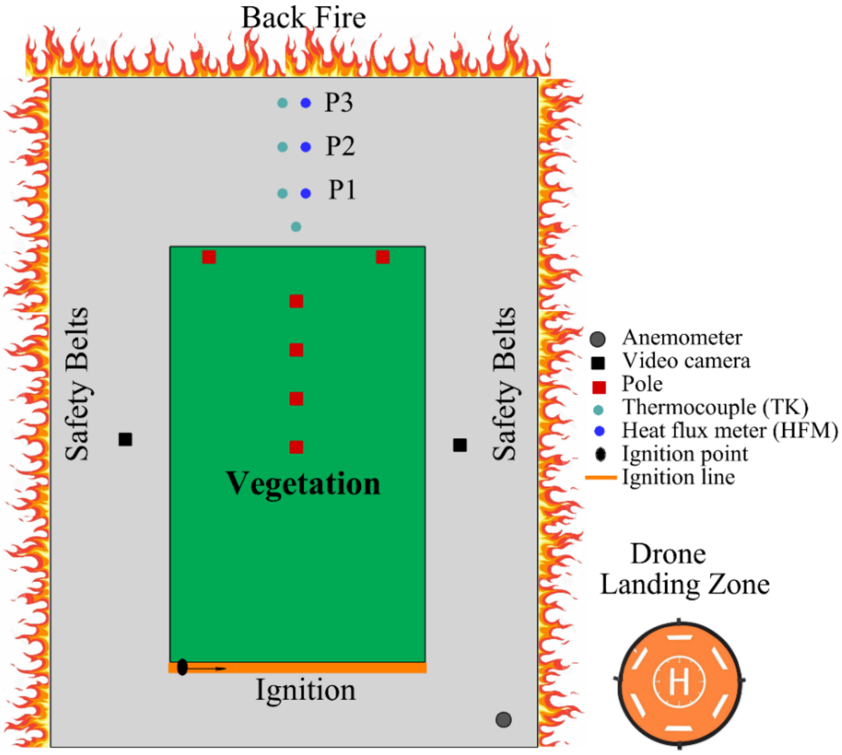


Figure 1- Schematic view of the experimental plot and the location of the measuring devices.

2.2. Characterization of the vegetation and meteorology

Physical properties of the vegetation are specific to the geographic area. Table 1 contains the main characteristics of the vegetation and meteorological conditions during the two burn campaigns. Fuel moisture content was evaluated after oven-drying fuel samples of dead and live fuel elements with diameter less than 6 mm at 60° for 48h (Awad et al. 2020). Fuel height was obtained after averaging 20 different measurements of the distance between the ground and the top of the vegetation. Ambient weather conditions were obtained less than 50 m away from the centreline of the plot, were a two-dimensional ultrasonic anemometer located at 3m above the ground recorder wind velocity and direction.

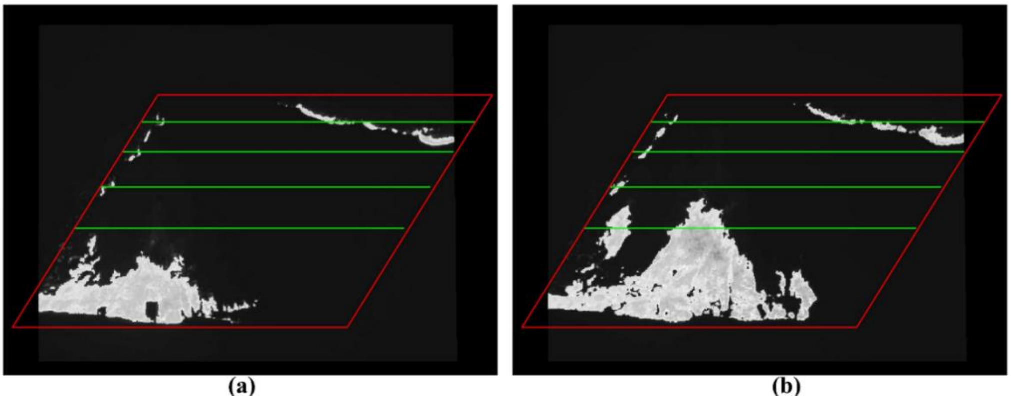
Table 1- Main average properties of Genista salzmannii vegetation and meteorological conditions

	Speluncatu March (2021)	**Speluncatu October (2021)**	**Letia March (2022)**
	Fuel Characteristics		
Fuel moisture content, FMC (%)	65	56	51
Fuel bed depth, *e* (m)	0.6	0.85	0.68
Fuel load, σ (kg/m^2)	1.8	1.79	2.67
Volume fraction, β	0.0031	0.0021	0.004
Surface-area to volume ratio, *s* (m^{-1})	3100		
Particle density, ρ_v (kg/m^3)	970		
Thermal capacity, *Cp* (J/kg/K)	1648		
Yield heat, ΔH_c (J/kg)	1.8620×10^7		
Thermal emissivity, ε	1		
Vegetation family shape	Cylindrical		
	Meteorological and topography conditions		
Average wind speed U_3 (m/s)	1.67	1.3	1.3
Ambient temperature *T* (°c)	6	18	15
Relative humidity *RH* (%)	82	53	36
Terrain slope value (°)	28	21.6	15.6

2.3. Experimental evaluation of fire parameters

2.3.1.ROS

The ROS represents one of the main parameters that characterize wildland fire behaviour. Fire front propagation is recorded using a drone located at a height of about 100 m, in order to determine the time needed by the fire to cross between the prefixed poles placed in the field. This allowed the evaluation of the ROS when the fire reaches a steady state propagation as shown in Figure 2.


(a) (b)

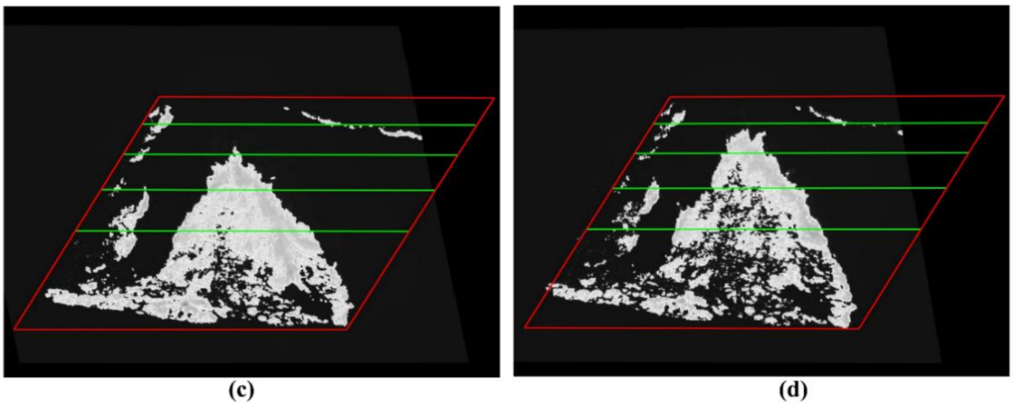


Figure 2- Infrared images of the fire front travel between equidistant positions (the green lines passing through prefixed poles) at different times.

2.3.2.Fireline intensity

Fireline intensity is estimated experimentally based on the Byram formulation: $I_{BExp} = \Delta H_c . w_a . ROS$, where $w_a = \mu \sigma$, with μ the percentage of the fuel weight actually consumed in the active flaming front and effectively contributed to fire propagation and ΔH_c represents the vegetation heat yield. This experimental method is often inaccurate because it is based on visual estimation of the burned vegetation during the fire (Alexander and Cruz 2020).

2.3.3.Heat fluxes

Concerning the fire impact evaluation, total and radiant heat fluxes were measured using three transducers (Figure 3) calibrated by the manufacturer in the range 0-200 kW/m^2, fixed on 0.5 m high supporting rods located at different positions from the upper limit of the vegetation plot.

Figure 3- Radiant and total heat flux sensors and thermocouple fixed on supporting rod and protected by aluminum foils.

3. Numerical method

3.1.Numerical modelling

Numerical simulations were conducted using a fully physical model, based on multiphase formulation, namely FireStar2D (Morvan and Dupuy 2001, 2004; Morvan et al. 2008, 2009; Morvan 2013; Awad et al. 2021). This model was validated from calculations carried out different scales and compared with experimental results, so it appears to be suitable for operational works since it provides valuable results and requires less simulation time compared to the 3D models. The main parameters of the computational domain and the vegetation layer is given in Figure 4. Both the solid-phase and the fluid-phase grids were characterized by cells sizes below the radiation extinction length scale (Morvan 2011; Morvan et al. 2013) given by $4/s\beta$, in order to avoid fire extinction especially in the case of radiation-dominated fire propagation. Simulations were carried out for a 10 m open wind speed U_{10} by assuming a one-seventh power wind velocity profile. The domain inclination angle was specified through two non-zero components of gravitational acceleration: $g_x = -g\sin(\alpha)$ and $g_z = -g\cos(\alpha)$, where $g = 9.81\text{ m/s}^2$ is Earth gravity.

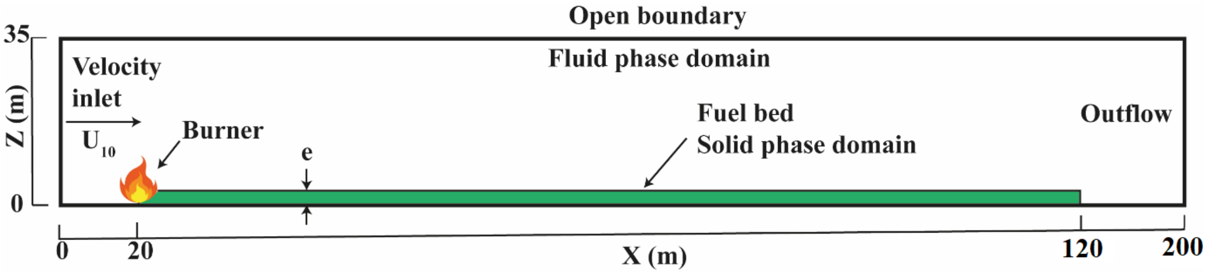


Figure 4- Computational domain and boundary conditions used in the 2D simulation of the experimental fire.

3.2. Numerical evaluation of fire parameters

3.2.1. ROS

Numerical prediction of the ROS using FireStar2D is obtained from the position of the pyrolysis front at the fuel-bed surface. It is the slope of the curve shown in Figure 5, once fire propagation had become steady.

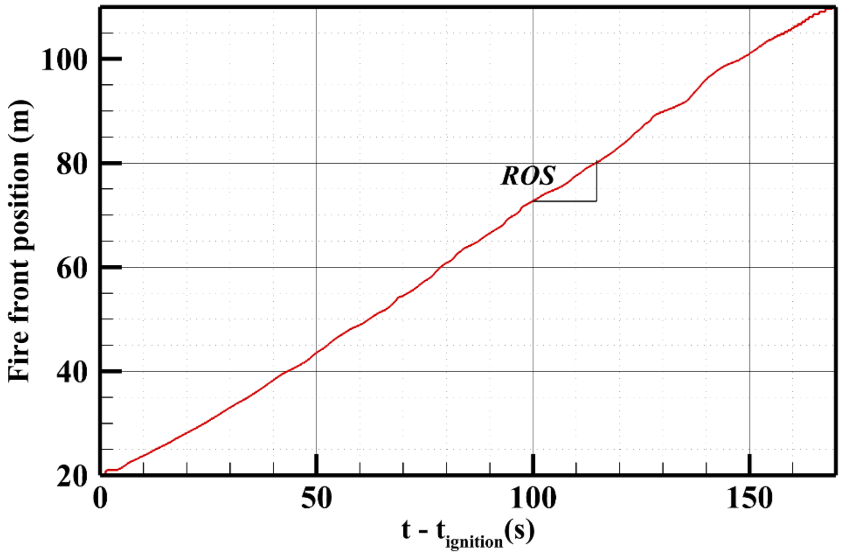


Figure 5- Position versus time of the furthermost point of the pyrolysis front at the fuel-bed surface obtained by FireStar2D after ignition at t = 30 s.

3.2.2. Fireline intensity

Numerical evaluation of fireline intensity is based on the following formulation: $I_{BNum} = \dot{m}\,.\,\Delta H_c$. Numerically, there is no difficulties to evaluate the vegetation degradation rate $\dot{m}$ as in the experimental method, where it is evaluated in this case by doing the summation of mass losses due to pyrolysis and charcoal combustion.

3.2.3. Heat fluxes

FireStar2D allows the evaluation of radiative and convective heat fluxes received by the targets, and assesses the heat fluxes recorded by the flux meters located ahead of the fire front. Convective heat flux is evaluated using Newton's law of cooling (Owen 2009), given by the following equation: $Q_{conv} = h_{\text{conv}}(T_0 - T_a)$, where $(T_0 - T_a)$ represents the difference between the gas mixture temperature and the target temperature (assumed to be the ambient temperature) and h_{conv} is the convective heat transfer coefficient.

4. Results and discussion

In this section, the results of the burns campaigns of Speluncatu and Letia will be presented. In this context, a comparison between experimental and numerical results concerning the ROS, and fireline intensity are shown in Table 2. Radiant and total heat fluxes received by the transducers located ahead of the vegetation area were registered when the fire front reached the end of the plot. During the burn campaign in October, backfires conducted by the firefighters to protect the burning zone were so close to the sensors, which have affected the measurements during fire. In this case, only heat flux measurements during March (2021) in Speluncatu and March 2022 in Letia were investigated, and compared with numerical predictions. Thus, time-averaged ratios (experimental and numerical) of the radiative heat fluxes to the total heat fluxes (i.e., convective and radiative), evaluated for the three flux meters are shown in table 3.

Table 2- Experimental and numerical results for the two burns campaigns in March and October.

	Speluncatu March (2021)		**Speluncatu October (2021)**		**Letia March (2022)**	
	Experimental	**Numerical**	**Experimental**	**Numerical**	**Experimental**	**Numerical**
ROS (m/s)	0.45	0.5	0.38	0.47	0.21	0.29
Fireline intensity (MW/m)	10.5	7.7	10.8	9.9	10.44	9.5

Table 3- Time-averaged ratio of the radiative heat flux to the total one evaluated experimentally in March, and with FireStar2D at the different target positions.

	Speluncatu March (2021)		**Letia March (2022)**	
Position	**Q_{rad}/Q_{tot} FireStar2D**	**Q_{rad}/Q_{tot} Experiment**	**Q_{rad}/Q_{tot} FireStar2D**	**Q_{rad}/Q_{tot} Experiment**
1	0.796	0.845	0.91	0.94
2	0.993	0.971	0.95	0.99
3	0.961	0.93		

Concerning the rate of spread, results show an agreement between experimental and numerical evaluations with a certain difference may be due to numerical considerations: (1) numerically, a homogeneous fuel bed is considered; (2) in 2D simulations, the fire front is considered as a uniform thermal barrier, while the fire front is in reality structured as a succession of peaks and troughs, allowing for the air flow to find a way across it (Frangieh et al. 2020). Concerning heat fluxes evaluation, both numerical and experimental heat fluxes reported in Table 3, show the same order of magnitude for the calculated ratios and they both reveal the dominance of the radiation heat transfer contribution at different targets positions.

Concerning fireline intensities, results show that these fires conducted in winter and autumn are high intensity fires where fireline intensities (numerical and experimental) exceeds the value of 7 MW/m, despite the unfavorable conditions (low wind speeds, high FMC and RH). Knowing that the fireline intensity is an index to characterize fire severity rating, the considered fires fall then into the "very high" fire severity (Cheney 1981). Fire severity also depends on fire residence time (Cruz et al. 2013) related to the ROS. In general, due to the important slope, fire moves fast, and the residence time becomes relatively small, which does not allow reaching a high percentage of fuel consumption, especially for high fuel moisture content (>40%) (Dahale et al. 2013). These three experiments confirm the fact that a fire can exhibit a dangerous behavior of a high intensity fire, even in winter, because it occurs along a steep slope, and for a high fuel load especially for Letia experiment. The presence of a slope induces a pressure gradient between the burned and the unburned zone due to the changes in the capacity of air entrainment. The Coanda effect is a reaction to this pressure difference (Sharples et al. 2010), where the fluid flow tends to be attached to the propagation surface. Due to the important slope, the Coanda effect is reinforced by a component of the buoyancy force acting in the x-direction, g_x. Consequently, the flame becomes more inclined toward the ground, which increases the heat transfer between the hot gases and the unburned vegetation, resulting in a fire acceleration and higher intensity fire (Sharples et al. 2010; Sánchez-Monroy et al. 2019). In addition, fireline intensity estimation is directly related to fuel load that contributes to the fire front propagation. Thus, important values of slope angles and fuel loads can explain the high intensity fires obtained during these different campaigns despite the unfavorable propagation conditions.

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