RATE OF SPREAD OF SURFACE FIRES UNDER NO WIND AND NO SLOPE CONDITIONS. DETERMINATION OF TWO CRITERIA FOR FIRE EXTINCTION

B. Moretti[1], J.-H. Balbi[1], C. Rossa[2,4], J.-L. Rossi[1], D. Cancellieri[1], D.X. Viegas[2,5] and A. Simeoni[3]
bmoretti@univ-corse.fr
[1]Université de Corse, Systèmes Physiques pour l'Environnement U.M.R.-C.N.R.S. 6134 Campus Grossetti, BP 52 20250 Corte, France
[2]Centre of Studies on Forest Fires/ADAI – University of Coimbra, Portugal
[3]Department of Fire Protection Engineering, Worcester Polytechnic Institute, USA
[4]School of Technology and Management, Polytechnic Institute of Leiria, Portugal
[5]Department of Mechanical Engineering, University of Coimbra, Portugal

Abstract
The first aim of this work is to provide an analytical expression to calculate the rate of spread of surface fires under no wind and no slope conditions. A previous simplified model was improved for this particular case of fire propagation. The test of this proposed model was performed by using two complete sets of experimental results with several fuel beds and variable parameters such as moisture content or bulk density. The second aim of this article is to highlight two conditions that allow stopping a fire: the low leaf area and the high value of the moisture content.

Introduction

Fires are the major source of forest destruction in the Mediterranean basin. Fire risk evaluation is of paramount importance in regions such as the Mediterranean, where a sharp increase of fire events in forests has been observed over these last years [1]. Fire spread models and wildland fire calculation systems have been designed in many scientific studies in the last six decades. Forest fire modelling deals with several different approaches [2, 3]. Following the classification set up by Perry [4], three kinds of modelling can be defined in accordance with the methods used in their construction. The simplest models are the empirical ones, which do not involve physical mechanisms [5]. Semi-physical models [6] are based upon the conservation of energy, but they do not distinguish the heat transfer mode. Finally, physical models differentiate the various kinds of heat transfer in order to predict the fire behaviour [7]. Among them, multiphase modelling, which takes into account the detailed physical phenomena involved in fire spread, represents the most complete approach developed so far [8, 9]. The problem of the determination of the rate of spread of surface fires under no wind and no slope conditions was studied for a long time using the previous approaches [10, 11]. Nevertheless, these approaches do not provide an expression of this rate of spread (R_o) with the various characteristics of the fuel beds strata: surface mass of fuel, moisture content, high calorific value, surface to volume ratios etc…

It is the first aim of this work. For that purpose, a simplified model was used [7] and improved for this particular case of fire propagation under no slope and no wind. To test the proposed model, it was compared by using two complete sets of experimental results: (i) the first series was made by C. Rossa and R. Oliveira with four different combustible media and variable parameters (moisture content, bulk density…) [12, 13] (ii) the second series was supplied by Catchpole *et al.* [14] and studies fire propagation on three different fuel beds. These fuel types were chosen as reasonable approximations to the natural fuel bed. The expression of R_o is necessary for most of the semi-physical models which provide the rate of spread from fuel and environmental variables by using a constant factor. For example, the model presented by Rothermel [6] has been widely used. In the Rothermel model, functions of wind velocity and slope are added and then multiplied by the rate of spread for a no wind, no slope fire (R_o). It is the basic model for the Behave computer system to predict fire behavior [15].

The second aim of this article is to highlight two conditions that allow stopping a fire: the low leaf area and the high value of the moisture content.

Model development

The simplified surface fire spread model

The simplified surface fire spread model was developed until 2007. Any reader interested by a complete description of this model development may refer to a previous work [7]. It predicts fire behaviour with a computational time faster than real time and it provides a good approximation of the fire front perimeter [16].

This relationship of the fire spread rate (R) across an equivalent homogeneous combustible medium and under slope and wind conditions is obtained by using a thermal balance assessment in the combustible zone downstream to the fire front. This relationship is the sum of two terms. The first one, R_b, evaluates the radiant heat flux impinging on the unburned fuel ahead of the fire front and is due to the flame base and the embers.

The second one determines the radiant heat flux which comes from the flame body. γ represents the tilt angle. This angle is calculated using the local slope (α), the wind speed which is normal on the fire front (U) and the upward gas velocity (u_o). If fire propagations under no wind and no slope conditions are considered (α=0 and U=0), the tilt angle value is equal to zero (γ=0) then an analytical expression for the rate of spread without wind and without slope is obtained:

$$R_b = \frac{e}{\sigma} \frac{\varepsilon_b B T^4}{C_p \Delta T + m \Delta h} \qquad (1)$$

with $\Delta T = T_i - T_a$.

Rate of Spread without slope and without wind

R_b is the rate of spread without slope and without wind evaluated using the simplified model aforementioned. However, several studies [17, 18 and 19] showed a discontinuity at the point U=0 for the experimental curves representing the rate of spread as a function of the wind speed. The explanation of this difference is the following one: while the tilt angle value (γ) is superior to zero, the flame is tilted by the wind towards the unburned zone of the fuel bed. Downstream, there is a wind induced (U_i) by the fire front. But, the effect of this cooling produced by the fresh air stream going from the unburned part to the flame is reduced. Indeed, this induced wind doesn't reach the embers and the lower part of the flame. So, this cooling phenomenon doesn't have any influence on the fire front rate of spread. On the other hand, when the wind is equal to zero, as the burned zone has a pressure slightly lower than the unburned part of the vegetation, the flame tilts towards the burned fuel bed (see Fig. 1). So, the cooling effect on rate of spread is noticeable. This is why one can notice the value of the rate of spread evolves from R_b for $\gamma=0^+$ to R_o for $\gamma=0$.

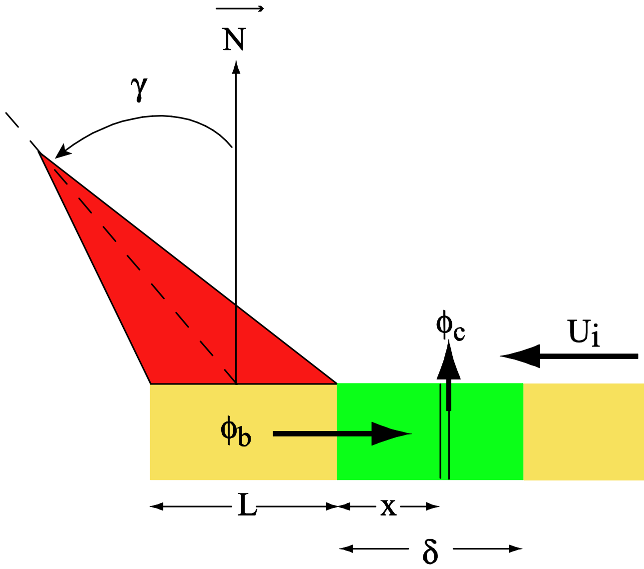

Figure 1. Schematic view of the radiance and convection contributions under no wind condition (U = 0 m/s).

Improvement of the model

In order to establish a relationship between Ro and R_b, a preheating thermal balance is applied. This thermal balance takes into account the radiant heat flux and the air cooling effect which are respectively due to the flame base and the induced wind. So, downstream to the flame, the heat transfer mechanisms in the vegetal stratum can be written as:

- Radiation coming from the base of the flame:

$$\phi_b(x) = e\,\varepsilon_b\,B\,T^4\,(1-\frac{x}{\delta})\,\mu \quad for \quad x \le \delta \tag{2a}$$

$$\phi_b(x) = 0 \quad for \quad x > \delta \tag{2b}$$

As mentioned in [20] the flame base emissivity for a wildland fire is assumed to be equal to $\varepsilon_b = 1$. The flame temperature is calculated using the model's result and the optical fuel depth can be calculated with the expression below:

$$\delta = \frac{4}{s\,\beta} \tag{3}$$

where s and β are respectively the surface/volume and the packing ratio. μ is a parameter determined assuming the hypothesis that all the radiation emitted by the flame is absorbed in the combustible medium:

$$\int_0^{\delta} \phi_b(x)dx = e\,B\,T^4 \tag{4}$$

Hence, after some calculations, the following relationship is obtained:

$$\mu = \frac{2}{\delta} \tag{5}$$

- Air cooling effect, convection heat transfer mechanism:

$$\phi_C(x) = c^*\,U_i^{\frac{1}{2}}\,(T(x) - T_a) \tag{6}$$

where

$$T(x) = T_i - (T_i - Ta)\frac{x}{\delta} \quad for \quad x \le \delta \tag{7a}$$

$$T(x) = Ta \quad for \quad x > \delta \tag{7b}$$

- Amount of energy to dry out the vegetal:

$$\phi_e = \Delta h \frac{d}{dt}(m\sigma) \tag{8}$$

The thermal balance is written with the assumptions described herein:

$$\sigma C_p \frac{dT}{dt} = e B T^4 (1 - \frac{x}{\delta})\frac{2}{\delta} - c^* (T_i - Ta)(1 - \frac{x}{\delta}) U_i^{\frac{1}{2}} - m \Delta h \frac{d\sigma}{dt} \tag{9}$$

Considering that $dx = R_o \, dt$ and by integrating onto the optical depth δ, the following analytical expression can be determined for the rate of spread:

$$R_o = \frac{e}{\sigma \left(C_p \Delta T + m \Delta h\right)} \left(B T^4 - c^* \Delta T \, U_i^{\frac{1}{2}} \frac{2}{S} \right) \tag{10}$$

where $S = \beta s e$.

Now, using the relationship:

$$\tan \gamma_i = \frac{4U_i}{S u_{oo}} \tag{11}$$

This angle γ_i is due to a difference of pressure between the burned and unburned zones of the vegetation. It is assumed that it has a constant value ($\gamma_i \approx 15°$). So, the induced wind U_i is proportional to S. Eventually, the rate of spread can be written:

$$R_o = R_b \left(1 - \left(\frac{S_e}{S} \right)^{\frac{1}{2}} \right) \tag{12}$$

where

$$S_e = \left(\frac{c}{B T^4} \right)^2 . \tag{13}$$

So under no wind and no slope conditions, the expression (12) takes the place of the relationship developed in [7]. Furthermore, in order to evaluate the temperature T, a thermal balance on the flame is applied. After some calculations, the following expression is found:

$$T = T_a + \frac{\Delta H \left(1 - \chi_o\right)}{\left(s_t + 1\right) C_{pa}} \tag{14}$$

Marginal burning

By considering the expression (12), one can deduce that if the value of S is not as high as the value of the constant S_e, fire propagation can't occur (R_o must be a positive number). Furthermore, one can note that this rule is true whatever the value of the moisture constant.

To test this assertion, it was compared with some experimental results performed under no wind and no slope conditions:

- Wolff *et al.* results [21] This set of experimental data concerns laboratory-scale experiments. The burning of thin fuels in the presence of an aiding wind was examined in a wind tunnel. Nearly two-hundred tests were conducted with several wooden fuel elements and with 5 fuels loads: 0.11, 0.22, 0.32, 0.44 and 0.88 kg/m^2. Wolff *et al.* show that, if the fuel load is less than 0.44 kg/m^2, the fire is unable to spread. So, it is possible to assess that a "critical" fuel load (σ_e) can be find between 0.32 and 0.44 kg/m^2. Now, using the relationship: $Se = \sigma_e s / \rho_v$. Hence, the constant S_e is calculated for these two limits:

  $$1.3 \le Se \le 1.7 \qquad (15)$$

- Butler *et al.* results [20] These experiments were performed in homogeneous and plane fuel beds made with shredded aspen (*Populus tremuloides*). Propagation was performed using several fuel depths (*2.5 cm< e <15 cm)* and several packing ratios ($0.005<\beta<0.03$). These results indicate that there is only one case without propagation: $e = 2.5\ cm$ and $\beta = 0.005$. The fuel leaf area (S) is 1.5 and the last value is 3. So, the value of the constant S_e is necessary between these two limits:

  $$1.5 \le S_e \le 3 \qquad (16)$$

Expression (12) of the rate of spread under no wind and no slope allows us to understand this non-spread phenomenon, even though the moisture content of the fuel is low: this means that the energy loss due to the induced wind is higher than the energy radiated by the base of the flame. This condition should not be confused with the inability for a fire to propagate due to a too high moisture content of the combustible. This extinction criterion (moisture extinction) is the subject of the next paragraph.

Moisture extinction

Expression (12) does not translate the existence of a critical value of the moisture content (m_e). If the moisture content (m) is lower than this critical value, fire is unable to propagate. The expression (12) was improved to figure out this significant factor affecting fire spread through surface fuels beds. Until now, the hypothesis of an emissivity equal to the unity (ε_b=1) has bee, validated. However, this assertion is not always verified. If the length of the inflamed vegetal L (see Fig. 1) is greater than the optical depth (δ) this assertion is true. But, if L< δ this emissivity is necessary lower than the unity. Indeed, leaf area reduced to burned-unburned interface is smaller than the actual surface. This can be translated into a law:

$$\varepsilon = \begin{cases} \dfrac{L}{\delta}, & L < \delta \\ 1, & L \ge \delta \end{cases} \qquad (17)$$

Now, using the relationship: $L = R_O \tau_O$. Hence, considering the case L≥δ, the expression (17) can be written, using $\tau \ge (\tau_o / s)$:

$$R_o \tau \ge \delta s \qquad (18)$$

If expressions (3) and (12) are inserted in (18) and after some calculations, the following expression is obtained:

$$m_e = \frac{\tau_o B T^4}{4\rho_v \Delta h}\left(1-\left(\frac{S_e}{S}\right)^{\frac{1}{2}}\right)-\frac{C_p \Delta T}{\Delta h} \tag{19}$$

The expression above shows that the critical moisture content (m_e) depends on the nature of the combustible medium (ρ_v, C_p) but also on the structure of the medium stratum (S). Hence, expression (12) must be rewritten to take into account the two previously defined regimes, *i.e.* $L < \delta$, and $L \geq \delta$:

$$R_o = R_b\left(1-\left(\frac{S_e}{S}\right)^{\frac{1}{2}}\right)\Gamma(m-m_e) \tag{20}$$

where $\Gamma(m-m_e)$ is the unit step function. This function can be given by the expression below:

$$\Gamma(m-m_e) = \begin{cases} 1, & m < m_e \\ 0, & m \geq m_e \end{cases} \tag{21}$$

Thus, one can consider two conditions that lead to extinguish fire propagation: (i) the low leaf area ($S<Se$). One can notice that in this case the fire can't spread whatever the value of the moisture content, (ii) the high value of the moisture content ($m>m_e$). Nevertheless, expression (21) shows that S is an argument of the moisture content m_e. Moreover, this relationship highlights the fact that if S decreases, then m_e will decrease and fire spread more often becomes impossible.

Experimental program to determine the ROS

Overall information

Most of the laboratory experiments results presented in this work are contained in the experimental program, presented in Rossa [12], conducted in the Laboratory of Forest Fire Research of the University of Coimbra, located in Lousã, in a total of 155 experiments. Although some experiments aimed at evaluating the fuel load and moisture content influence in fire spread on level ground in the absence of wind, most of that experimental program was made with the purpose of analysing fire spread under the influence of wind or slope. However, for those experiments, a reference test for measuring the rate of spread in the absence of wind and slope was also made, in order to have a reference rate of spread. The experimental data analysed in this paper concerns the experiments performed with no wind and slope. The remaining tests were retrieved from Oliveira [13].

Fuel beds

The burning area was always around 1 m^2 large. Four fuel beds were used: dry straw, *Pinus pinaster* dead needles, *Eucalyptus obliqua* leaves and *Eucalyptus globulus* slash, in order to simulate respectively a flashy fuel and three slower burning fuels. Great care was taken in the preparation of the fuel beds in all tests in order to ensure consistency in the whole program as it is recognized that small variations in fuel bed properties are of paramount importance in assuring the reproducibility of a given laboratory experiment [22].

The fuel load used in the present tests was measured on a dry basis. Although fuels loads of 0.8 and 1.0 kg/m^2 were tested, in most of the experiments a 0.6 kg/m^2 fuel load was used. The same load is used, for example in the laboratory experiments reported in [23]. This value is similar to that of 0.5 kg/m^2 reported in [24] as an average fuel load found in grasslands. Fuel loads of 0.5 kg/m^2 also correspond to the average value in the field experiments reported in Byram [25] performed in mixtures of grass and pine needles.

Fuel moisture content was measured to determine the fuel weight necessary for each test using one or more samples in a fuel moisture analyzer *A&D MX-50* (0.1 % accuracy) that retrieved its value in about ten minutes. After weighing the required fuel in a scale *A&D HW-100KGL* (20 g accuracy) it was spread homogenously on the test rig, maintaining a regular fuel bed height between experiments with the same fuel in order to maintain the bulk density as constant as possible.

Procedures

All tests were prepared according to a previously defined and written protocol adopted in our Laboratory for this type of experiments [26]. Fuel load, fuel homogeneity and fuel bed bulk density were controlled and maintained more or less constant during the experiments without much difficulty, although in some experiments the bulk density was not measured. On the contrary as fuel moisture content was not conditioned, varying as a function of the ambient air temperature and relative humidity, it had to be monitored carefully during the preparation and before each experiment. Air temperature and relative humidity were monitored as well (except for some experiments, due to problems with the weather station).

Strings were stretched over the fuel bed at a constant spacing in order to determine the rate of spread, by registering the time instant at which each string was broken by the advancing fire. The distance between strings varied between 10 and 25 cm according to the test rig in use, and the number of strings depended upon the size of the fuel bed. The number of strings was always above four. In each test ignition was initiated by creating a nearly instantaneous line of fire, parallel to the strings, using a wool string soaked in gasoline.

The rate of spread of the most advanced part of the fire front was estimated from the known times that it took the fire to burn each string. The value of the rate of spread for all tests was computed by linear fit using least squares error. The mean value of r^2 was 0.996 with a standard deviation of 0.004 and always greater than 0.974.

Determination of the specific heat capacity

Heat capacity is an intrinsic property of a material, defined as the amount of heat required to increase the temperature of a system or substance by 1°C. Heat capacity is usually expressed in J/Kg/C. The specific heat capacity *Cp* is besides the thermal conductivity λ and the density ρ one of the major physical properties required when analysing material thermal behaviour. There exists a large number of test methods to determine *Cp*. In our case all experiments were performed on a pyris 1 DSC perkin elmer® based on the power compensated principle. The method used “StepScan Cp” is an add-on to the Pyris software. It takes data collected by a method containing at least one StepScan: a heating ramp between two isotherm steps calculates the specific heat. A StepScan facilitates collection of accurate specific heat data by measuring repeatedly the heat flow for a known amount of the sample at a constant heating rate. StepScan data acquired with 1-minute isothermals, the criterion set at 0.02 mW, the scan rate of 30°C/min from 60°C to 61°C, 100 repetitions. A low value temperature modulation was chosen so as to not create interference caused by changes of kinetically controlled processes. Oxidative atmosphere (N_2 80% / O_2 20%) was selected in all experiments at 30 ml/min. Sample was die-cut at the exact size of the crucible, its mass being around 2mg. For apparatus calibration the following steps were performed in order to obtain the specific sapphire heat. The sapphire calibration standard has a NIST certificate. Diameter is 6.5 mm; height 0.9 mm and weight 28 mg. The sample pans used were also provided by Perkin Elmer® and have an outside diameter of 6.6 mm and weigh on average 18.9 mg.

Results

Comparison between literature experimental results [15] and the proposed model

In order to determine the rate of spread for different fuels beds, several experimental fires were conducted over a wide range of conditions in a wind tunnel. Three fuels were selected: needles of ponderosa pine (*Pinus ponderosa*), and two size of poplar excelsior (*Populus tranulos*), regular (0.8 x 0.4 mm in cross-section) and coarse (2.5 x 0.8 mm in cross-section). These fuels type were chosen to approximate the pine forest litter and the fine shrub and grassland.

Determination of the convection parameter c

Excelsior species were selected because they have the advantage of having all the same parameters except for the surface to volume ratio (s). Expression (20) indicates a linear relationship between βR_o and $1/S^{1/2}$. So, curves of the form

$$R_o = a - b\left(\frac{1}{S}\right)^{\frac{1}{2}} \tag{24}$$

are selected. The estimates for a and b are a = 4.46 10^{-4} m/s and b = 6.46 10^{-4} m/s. While c = a/b, the value of the convection parameter c is calculated using these two previous values: c = 0.69.

Testing the model

The model is now tested on the three fuels previously selected: needles of ponderosa pine, and two sizes of poplar excelsior. Value of convection parameter c was found above using only the two Excelsior species (c = 0.69). The different fuel properties are given by *Catchpole et al. [15]:* ρ_v, Δh, m, C_p and s. The fraction radiation χ_o is assumed to be equal to 0.3. The temperature of the base of the flame is evaluated using the expression (14). Fig. 2 shows the predictions from the studied model and the observed values.

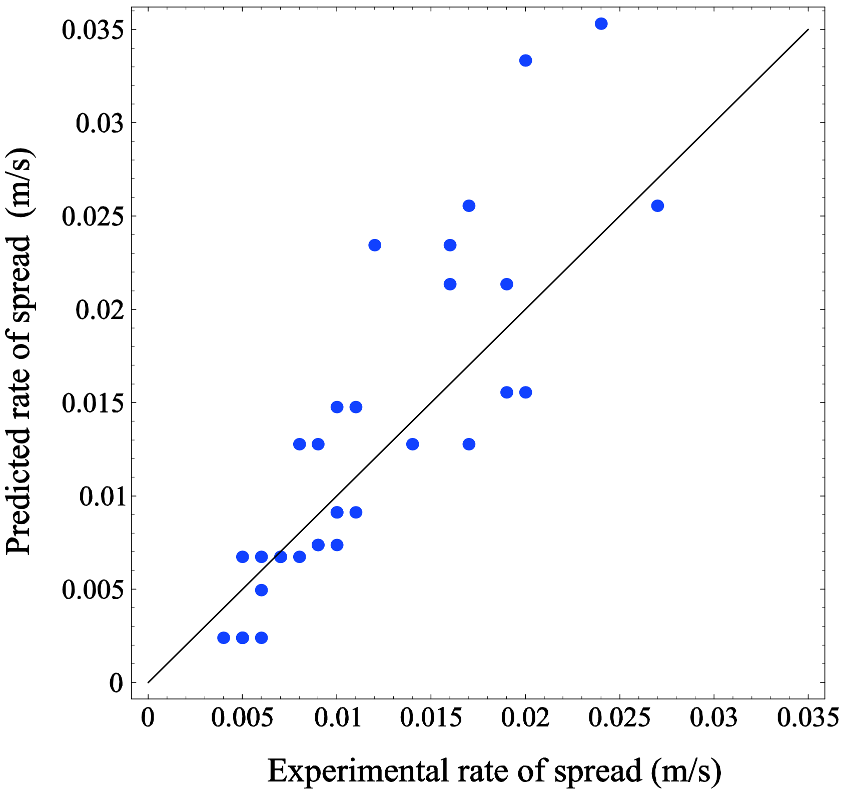

Figure 2. Comparison between predicted and experimental rate of spread for three fuels: needles of ponderosa pine, and two size of poplar excelsior [15].

The quality of the estimates from the proposed model was evaluated using a statistical performance measures. From the statistical measures, the normalized mean square error (NMSE), the fractional bias (FB) and the coefficient of determination (R^2) which are the most commonly used for model evaluation [27] were chosen for this present analysis. These statistical measures are detailed in appendix. The values of NMSE, FB and R^2 can be seen in Table 1. First of all, it can be observed that the model has a fairly good correlation and a small deviation. Secondly, it can be noted that this approach underestimates the experimental values. The variation of predicted values by the models must be attributed to the fact that the experimental data were obtained in fires under a wide range of conditions. Though, despite the complicated nature of this study, these approaches produce fairly good predictions for the rate of spread. The agreement between the models and these experimental values lends credibility to the model presented herein.

Comparison between experimental results [13, 14] [20, 21] and the proposed model
A confrontation with some experimental results conducted in the Laboratory of Forest Fire Research of the University of Coimbra is presented in this section. The model is tested on four different fuel beds: dry straw, *Pinus pinaster* dead needles, *Eucalyptus obliqua* leaves and *Eucalyptus globulus* slash. Value of convection parameter c was previously found using only the two Excelsior species (c = 0.69). The different fuel properties are detailed in a dedicated table in appendix. The four specific heat of combustible fuel are determined using the methodology detailed herein. The fraction radiation is still assumed to be equal to 0.3. Figs. 3 illustrate a comparison of experimental results obtained using one of the four aforementioned fuel beds with the results of the model proposed here.

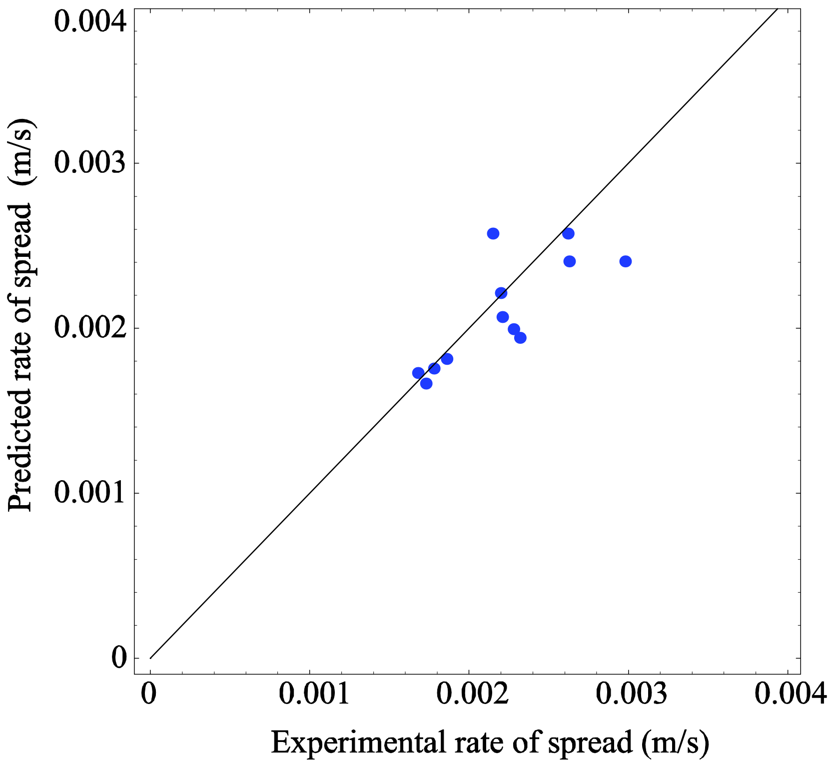

Figure 3. Comparison between predicted and experimental rate of spread for *Pinus pinaster* dead needles fuel bed *[20]*.

The statistical measures were computed for the entire data set (see Table 1).

Table 1. Statistical analysis.

	NMSE	FB	R^2
Catchpole et al. [15]	0.16	0.04	0.86
Rossa and Oliveira [13, 14]	0.02	0.04	0.96

First of all, it can be noted, that the same observations can be found: the model has a small deviation and this approach underestimates the experimental values. Secondly, it can be observed that the model has a better accuracy using these experimental results. It is certainly due to the fact that the experimental data were conducted in a laboratory under controlled conditions. Though, despite the complicated nature of this study, this approach produces fairly good predictions for rate of spread in no wind and no slope conditions.

Conclusion

The main goal of this study is to produce an analytical expression to calculate the rate of spread of surface fires under no wind and no slope conditions, which allows determining two conditions that permit to extinguish a fire: the low leaf area and the high value of the moisture content. The validation of this model has been done with several literature experimental results, and also for a set of fires at laboratory scale conducted in the Laboratory of Forest Fire Research of the University of Coimbra. The selected fuels were chosen to be reasonable approximations to natural combustible media. In all cases, it provides quite good results despite the number of species selected, and the wide range of conditions studied. So, this approach supplies an expression of the rate of spread (R_o) with the various characteristics of the fuel beds strata. So, the semi-physical models which supply rate of spread from fuel and environmental variables by using a constant factor can use this expression despite an experimental value.

Acknowledgments

The present work was supported in part by the French Ministry of Research, the Corsican Region and the CNRS, under Grant CPER 2007-2013. We also wish to thank Mr. Gonsolin for his English reviewing.

Nomenclature

A	model parameter, radiation contribution
B	Stefan-Boltzmann constant ($W/m^2/K^4$)
c, c^*	model parameters, convection contribution
C_p	specific heat of vegetative fuel (J/kg/K)
C_{pa}	specific heat of ambient air (J/kg/K)
e	depth of fuel bed (m)
m	moisture content (weight of water/total weight)
m_e	critical moisture content (weight of water/total weight)
$\vec{N}$	unit vector, normal to the fuel bed
R	rate of spread (m/s)
R_b	rate of spread due to the flame base radiation (m/s)
R_o	rate of spread under no wind and no slope conditions (m/s)
r_o	model parameter (m/s)
s	surface area to volume ratio (1/m)

S leaf area index
S_e critical leaf area index
T temperature flame base (K)
T_a ambient temperature (K)
T_i temperature of ignition (K)
Δh heat of latent evaporation (J/kg)
ΔH heat of combustion of fuel (J/kg)
U wind speed, normal to the fire front (m/s)
U_i induced wind (m/s)
u_o upward gas velocity (m/s)
x coordinate in space (m)

Greek

α local slope angle
β packing ratio
ε emissivity of the flame
ε_b emissivity of the inflamed stratum
ρ_v fuel load (kg/m^2)
γ flame tilt angle
δ optical fuel depth (m)
χ_o law for fraction radiation
ϕ_b amount of energy coming from the base of the flame (W/m)
ϕ_c convection contribution (W/m)
ϕ_e amount of energy to dry out the vegetal (W/m)
τ flame residence time (s)
τ_o model parameter (s/m)
Γ unit step function

References

[1] Pausas J.G., Llovet J., Rodrigo A., Vallejo R., “Are wildfires a disaster in the Mediterranean basin? - A review”, *International Journal of Wildland Fire* 17: 713–723 (2008)

[2] Sullivan A.L., “Wildland surface fire spread modelling, 1990–2007. 1: Physical and quasi-physical models”, *International Journal of Wildland Fire* 18: 349–368 (2009a)

[3] Sullivan A.L. “Wildland surface fire spread modelling, 1990–2007. 2: Empirical and quasi-empirical models”, *International Journal of Wildland Fire* 18: 369–386 (2009b)

[4] Perry G.L.W., “Current approaches to modelling the spread of wildland fire: a review”, *Progress in Physical Geography* 22: 222–245 (1998)

[5] McArthur A.G., “Weather and grassland fire behaviour. Australia Government Publishing Service”, *Australian Forest and Timber Bureau Leaflet N°100* (Canberra, Australia) (1966).

[6] Rothermel R.C., “A Mathematical Model for Predicting Fire Spread in Wildland Fuels”, *Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. Research Paper INT-115* (1972).

[7] Balbi J.H., Rossi J.L., Marcelli T., Santoni P.A., “A 3D physical real-time model of surface fires across fuel beds”, *Combustion Science and Technology* 179: 2511–2537 (2007)

[8] Mell W., Jenkins M.A., Gould J., Cheney P., “A physics-based approach to modelling grassland fires”, *International Journal of Wildland Fire* 16: 1–22 (2007).

[9] Morvan D., Méradji S., Accary G., "Physical modelling of fire spread in Grasslands", *Fire Safety Journa*l 44: 50– 61 (2009)
[10] Viegas D.X., Neto L.P.C., "Wall Shear-Stress as a Parameter to Correlate the Rate of Spread of a Wind Induced Forest Fire", *International Journal of Wildland Fire* 3: 177–188, (1991)
[11] De Mestre N.J., Catchpole E.A., Anderson D.H., "Uniform propagation of a planar fire front without wind", *Combustion Science and Technology* 65: 231–244 (1989)
[12] Rossa C.G.,"Dynamic model for fire behaviour prediction", *PhD thesis. Department of Mechanical Engineering*, University of Coimbra, Portugal (2009).
[13] Oliveira R.F., "Um estudo sobre os incêndios florestais ocorridos no Estado de Vitória (Austrália)", *MSc thesis. Department of Mechanical Engineering, University of Coimbra, Portugal* (2010) [in Portuguese].
[14] Catchpole W.R., Catchpole E.A., Butler B.W., Rothermel R.C., Morris G.A., Latham D.J., "Rates of spread of free-burning fires in woody fuels in a wind tunnel", *Combustion Science and Technology* 131: 1–37 (1998)
[15] Burgan R.E., Rothermel R.C., "BEHAVE: fire behavior prediction and fuel modeling system-FUEL subsystem", *Department of Agriculture, Forest Service, Intermountain Research Station. Gen. Tech. Rep. INT-167* (1984).
[16] Balbi J.H., Rossi J.L., Marcelli T., Chatelon F.J., "Physical Modeling of Surface Fire Under Nonparallel Wind and Slope Conditions", *Combustion Science and Technology* 182: 922–939 (2010)
[17] Mendes-Lopes J.M.C., Ventura J.M.P., Amaral J.M.P., "Flame characteristics, temperature-time curves, and rate of spread in fires propagating in a bed of *Pinus pinaster* needles", *International Journal of Wildland fire* 12: 67–84 (2003)
[18] Viegas D.X., "Slope and wind effects on fire propagation", *International Journal of Wildland fire"* 13, 143–156 (2004)
[19] Porterie B., Zekri N., Clerc J.P., Loraud J.C., "Modeling forest fire spread and spotting process with small world networks", *Combustion and Flame* 149, 63–78 (2007)
[20] Butler B.W., Anderson W.R., Catchpole E.A., "Influence of Slope on Fire Spread rate", *Department of Agriculture, Forest Service. Proceedings RMRS-P-46CD* (2007)
[21] Wolff M.F., Carrier F., Fendel F.E., "Wind-Aided Firespread Across Arrays of Discrete Fuel Elements. II. Experiment", *Combustion Science and Technology* 77: 261–289 (1991)
[22] Schuette R.D., "Preparing reproducible pine needle fuel beds", *USDA Forest Service, Intermountain Forest and Range Experiment Station Research Note INT-36* (1965).
[23] Van Wagner C.E., "Fire behaviour mechanisms in a red pine plantation: field and laboratory evidence", *Canadian Forest Service, Forestry Branch Departmental Publication 1229* (1968).
[24] Luke R.H. and McArthur A.G., "Bushfires in Australia", *Australia Government Publishing Service* (1978)
[25] Byram G.M., *Combustion of forest fuels. In 'Forest fire: control and use,* McGraw-Hill, 1959, pp. 61-89.
[26] Rossa C.G., "Protocol for the experiments made in LEIF in the scope of the ENB training given by CEIF", *CEIF / ADAI – University of Coimbra Internal technical report* (2009)
[27] Muñoz M., Arnaldo J., Casal J., Planas E., "Analysis of the geometric and radiative characteristics of hydrocarbon pool fires" *Combustion and Flame*, 139: 263-277 (2004)