Simulation of fire spread using

Physics-inspired and chemistry-based mathematical analogues

Alexandre Muzy[1], Dominique Cancellieri[2], David R.C. Hill[3]

(1) Research laboratory LISA UMR CNRS 6240, BP 52, Università di Corsica – Pasquale Paoli, Campus Mariani, F- 20250 CORTI, France.
(2) Research laboratory SPE UMR CNRS 6134, Università di Corsica – Pasquale Paoli, Grossetti, F-20250 CORTI, France.
(3) Research laboratory LIMOS UMR CNRS 6158, Blaise Pascal University, BP 10125, AUBIERE Cedex, France.

Corresponding author: a.muzy@univ-corse.fr

1. Introduction

Fire spread research is multi-objective. Foresters are usually interested in obtaining reusable pragmatic information on: fire dynamics, vegetation inflammability, the impacts of forest fires on vegetation, etc. Physicists [1] rigorously study the physics-based mechanisms involved in fire spreading. Using the terms and the models of thermodynamics, their aim is to fully understand *what* is a fire and *how* does it spread. Chemists focus on fuel and gas properties (not on the dynamics of fire spread.) Computer scientists usually implement the numerical solutions of mathematical continuous equations [2] and/or manage data-bases of experiments and simulation results [3]. They can also build models on their own through mathematical analogues without any physical or chemical foundations (mainly ellipses [4][5] or cellular automata [6].)

Every discipline develops idiosyncratic models, which avoid (or make difficult) interdisciplinary collaborations and lead to a dispersal of research efforts. Our scope here is to discuss the modeling contribution of each discipline involved in this study. The main mechanisms (mass loss in chemistry

and heat transfer in physics) are embedded in an original simulation model. Mass loss is studied in detail and an original model is presented. The modeling of heat transfers is achieved through mathematical analogues inspired from physics. In ecological modeling, occurrence risks and impacts of fires on vegetation are usually statistically analyzed [7]. Here, both structure and behavior of fire spreading are explicitly described in time through a simulation model.

2. Thermal degradation of fuels in chemistry

Thermal decomposition kinetics of biomass is an important key in thermochemical conversion processes. Thermal decomposition kinetics of biomass aims at studying the production of energy and chemical products [8][9][10]. In wildland fire, the rate of mass loss (due to thermal decomposition) determines the available volatile fuel in the flaming zone. To a lesser extent, the mass loss rate also determines the heat release rate (product of combustion heat and mass of fuel burned.) Therefore, the analysis of the thermal degradation of ligno-cellulosic fuels is decisive for wildland fire modelling and fuel hazard studies [11][12][13][14].

At an experimental level, many studies led to different degradation schemes in inert environment [15] but only a few were monitored in air atmosphere [16]. The whole process is complex and concerns solid and gaseous reactions. In solid-state, a variation in apparent activation energy may be observed for an elementary reaction. This is due to the heterogeneous nature of the solid or due to a complex reaction mechanism. This variation can be detected by isoconversional or model-free methods. The isoconversional analysis provides a fortunate compromise between the oversimplified but widely used single-step Arrhenius kinetic treatment and the prevalent occurrence of processes whose kinetics are multi-step and/or non-Arrhenius [17]. These methods allow estimating the apparent activation energy, at progressive degrees of conversion, for an independent model. Application of model-free methods was highly recommended in order to obtain a reliable kinetic description of the investigated process. The heat released from combustion causes the ignition of adjacent unburned fuel. Therefore, the analysis of the thermal degradation of lignocellulosic fuels is decisive for wildland fire modelling and fuel hazard studies [18].

Physical fire spread models are based on a detailed description of physical and chemical mechanisms involved in fires. Since the pioneering work of Grishin [15], these models incorporate

chemical kinetics for the thermal degradation of fuels. However, kinetic models need to be improved. The knowledge of the kinetic triplet (E_a, K_0 and n) and the kinetic scheme can help in predicting the rate of thermal degradation when the collection of experimental data is impossible in classical thermal analysis (high heating rates encountered in fire conditions).

For a mass loss modeling, based on the Arrhenius's law, we denote here the conversion degree defined as:

$$\alpha = \frac{m_0 - m(t)}{m_0 - m_\infty} \quad or\ \alpha = \frac{\Delta H(t)}{\Delta H_\infty} \tag{1}$$

Where α is the conversion degree, ΔH is the enthalpy of the reaction (kJ/g) and m is the mass loss ($\%$).

The rate of heterogeneous solid-state reactions can be described as:

$$\frac{d\alpha}{dt} = A\, e^{-E_a / RT} f(\alpha) \tag{2}$$

Where E_a is the activation energy (kJ/mol), A is a pre-exponential factor ($1/s$), t is the time (min), R is the gas constant 8.314 (kJ/mol), $f(\alpha)$ is the kinetic model reaction, and T is the temperature (K).

The temperature dependence of the constant rate is described by the Arrhenius equation. Galwey et al. [19] presented a theoretical justification for the application of the Arrhenius equation to the kinetics of solid state reactions. It is now recognized that this empirical equation represents the experimental rate data as a function of temperature, accurately and in both homogeneous and heterogeneous reactions [20]. More recently, some papers have demonstrated how a complete isoconversional kinetic analysis can be achieved using the dependence on activation energy, in association thermo-analytical data [21].

The parameters of the kinetics reaction were determined using the following procedure. Under non-isothermal conditions, in which a sample is heated at a constant rate, the explicit temporal dependence in Equation (2) is eliminated through the trivial transformation:

$$\frac{d\alpha}{dT} = \frac{A}{\beta} e^{-E_a / RT} f(\alpha) \tag{3}$$

We define $g(\alpha)$ as:

$$g(\alpha) = \int_0^{\alpha} \frac{d\alpha}{f(\alpha)} = \frac{A}{\beta} \int_{T_0}^{T} e^{-E_a / RT} dT = \frac{AE_a}{R\beta} p(x) \tag{4}$$

Where $x = \frac{E_a}{RT}$ and $p(x) = \int_{x_0}^{\infty} \frac{e^{-x}}{x^2} dx$, β is the heating rate (*K/min*), and T is the temperature (*K*).

Kinetics analyses are traditionally expected to produce an adequate kinetic description of the process in terms of the reaction model and the Arrhenius parameters. There are many methods for analyzing solid-state kinetic data. These methods may be classified according to the experimental conditions selected and to the mathematical analysis performed. Experimentally, either isothermal or non-isothermal methods are employed. The earliest kinetics studies were performed under isothermal conditions [22]. However, a major drawback of the isothermal conditions assumption is that a typical solid-state process has its maximum reaction rate at the beginning of the transformation. Several mathematical methods can be used to calculate the kinetics of solid state reactions: model-fitting and isoconversional (model-free) methods. A model-fitting method involves two fits: the first establishes the model that best fits data while the second determines specific kinetic parameters such as activation energy and pre-exponential factor using Arrhenius equation. The model-fitting approach has the advantage that only one TGA measurement is needed. However, almost any $f(\alpha)$ can satisfactorily fit the data by virtue of the Arrhenius parameters compensation effects and only a single pair of Arrhenius parameters results from the model-fitting method. Consequently, researchers give up this kind of method for the benefit of isoconversional methods, which can compute kinetic parameters without

modelling assumptions [23][24]. The isoconversional method has the ability to reveal the complexity of the process in the form of a functional dependence of the activation energy E_a on the extent of conversion α. The basic assumption of these methods is that the reaction rate for a constant extent of conversion, α, depends only on the temperature [25][26]. To use these methods, a series of experiments has to be performed at different heating rates [27]. The knowledge of E_a *vs.* α allows detecting multi-step processes and predicting the reaction kinetics over a wide temperature range. For this work we chose the method of Kissinger-Akahira-Sunose (KAS) [28] applied without any assumption concerning the kinetic model. The Kissinger-Akahira-Sunose method uses Doyle's approximation present in Equation (5):

$$p(x) \approx \frac{e^{-x}}{x^2} \tag{5}$$

Taking into account the approximation, the logarithm of Equation (4) gives:

$$\ln\left(\frac{\beta_j}{T_{jk}^2}\right) = \left[\ln\left(\frac{A_\alpha R}{E_a(\alpha_k)}\right) - \ln g(\alpha_k)\right] - \frac{E_a(\alpha_k)}{RT_{jk}} \tag{6}$$

Where $E_{a\alpha}$ and A_α are respectively the apparent activation energy and the pre-exponential factor at a given conversion degree α_k, and the temperatures T_{jk} are those which the conversion α_k is reached at a heating rate β_j. During a series of measurements the heating rates are $\beta = \beta_1 \ldots \beta_j \ldots$

The apparent activation energy was obtained from the slope of the linear plot of $\ln\left(\beta_j / T_{jk}^2\right)$ *vs.* $1/T_{jk}$ performed thanks to a Microsoft® Excel® spreadsheet developed for this purpose.

When the values of the apparent activation energy and the pre exponential factor were determined it was possible to reconstruct the reaction model [29]:

$$f(\alpha) = \beta\left(\frac{d\alpha}{dT}\right)_\alpha \left[A(\alpha)\, e^{\left(-E_a(\alpha)/RT(\alpha)\right)}\right]^{-1} \tag{7}$$

3. Simulation model and mathematical analogues of physics-based models

"Simulation models (…) implement (…) models in a simulation rather than modelling context. Mathematical analogue models are those that utilise a mathematical precept rather than a physical one for the modelling of the spread of wildland fire" [30]. Mathematical analogue models [31] firstly introduced the use of *Huygens' wavelet* principle in fire spread modeling. This kind of modeling considers ignition propagations as ellipses. *Cellular automata* approaches [32][33][34][35][36] compute simple mathematical rules to reproduce fire spreading. *Percolation*, in mathematics, considers transports through randomly distributed media. It is the "simplest example of fractal growth model" [37]. The latter study considers satellite images of wildland fires to model statistical properties of fire spreading. In artificial neural networks [38] weightings for each connection between the nodes is learnt through usual neural network learning rules. Physics focuses on the propagation of fire through heat transfers [39] (diffusion, convection and radiation), possibly integrating simplified chemical sub-models. However, no single model faithfully reproduces all heat transfers. Another perspective (the one chosen here) is to consider heat transfers as related to the mass loss of ignited fuels. The total heat released by ignited fuels depends on their burning mass (and loss rate.) Then, a part of the heat impinges on other fuels according to their distance, their moisture, the wind conditions, and topography (the other part of heat is transferred to the air.) This approach allows simplifying the modeling and simulation of heat transfers.

We propose here a mathematical model integrating all these parameter interactions. This model is based on the chemical degradation of fuel and inspired from physics.

3.1 Geometry of fire spread

As presented in Section 2, characteristics (energy released and received, mass loss) in a combustible sample can be studied through chemistry. The experimental protocol consists in submitting the combustible sample to a heating source, until ignition. A weighting apparatus is then used to measure the mass loss. A temperature sensor is used to measure the temperature in the fuel. The experiment (and the corresponding mathematics-based knowledge presented in section 2) is repeated for many

species of vegetation. The goal is to calculate the main mass loss characteristics of every species, according to the heating rate they are submitted to.

A difficulty arises for measuring heat transfers in the fuel and in the air. First, because it is difficult to determine the effective boundaries of "a flame." Second, because it is impossible to measure the temperature at every location within and around the fuel. Third, because both slope and wind consequences on fire spread are difficult to model. Physics attempts to achieve this goal [9]. However, there is no physical model able to reproduce precisely and faithfully all the mechanisms of heat transfers.

Therefore, it is usually convenient to achieve mathematical and computational analogues (without any physical assumptions) to build experiments of fire spread using discrete and continuous functions. The parameters of these functions do not have any physical foundations. In physics, although the modeling parameters benefit from a long history of mathematical modeling (validated by experiments), it should be noticed that their numerical value was determined under precise experimental conditions. These conditions are difficult (impossible?) to reproduce. They are always slightly different, or even incompatible with actual conditions of fire spreading.

Simulation and mathematics can be used to model the propagation of energy/heat in space. Virtual experiments are implemented. Parameter combinations are successively tested to fit (quantitatively and/or qualitatively) many fire propagations. These mathematical analogues can finally be used to feed physical and/or chemical models.

Another solution (the one investigated here) is to use chemical modeling to describe precisely the mass loss process according to the heat received by fuels. The geometry and heat influence of the fire front depending on many unknown correlated parameters, probabilities are used to provide more flexibility and robustness to fire spread modeling. Probabilities enhance flexibility because a range of many parameters will produce a mean area of propagations. A computational/mathematical model is built here using analogues of physical modeling of heat transfers.

We present here a wind-based ellipse model for the determination of the heat influence zone of burning sites. Inside this influence zone, the fuel mass degradation is considered through radiative influences. Finally fire brands, stochastically generated, are taken into account.

3.2 Stochastic wind effects

Wind (and slope) tilts the flames of a fire front thus increasing the heat influence area of the fire front, in the wind direction. The difficulty of modeling wind intensity and directions is due to the fact that wind blows in a squally fashion. Wind distribution, speed and directions are highly erratic. A wind blowing at a speed of *30km/h* is an average of squalls below and above *30km/h*. Besides, a northeast wind is not, dynamically, blowing northeast all the time. Finally, because of vegetation and topographic shapes, vegetation porosity, local and global winds have very different directions and speed. More than humidity and slope characteristics, winds need to be modeled stochastically.

The heat influence area of ignited cells can be determined mathematically through ellipses [5]. A physics-based and computational-based model has been presented in [40]. The notion of impact parameter and ellipses is used through small world networks. “The impact parameters can be either identical to the characteristic lengths *lx* and *ly* [axis of the ellipse] directly related to the radiative/convective impact of the burning site (deterministic case) or generated following a Poisson-like distribution based on these lengths (random case) [41]. They are dependent on fire and fuel conditions and expressed in an arbitrary length unit (δl) corresponding to the lattice parameter. A high value of the impact parameter ratio *ly/lx* corresponds to a strong anisotropy of the front shape induced by the terrain slope and/or wind effects in the *y*-direction.”

In our model, the wind lengthens the shape of the ellipse in the wind direction. Width *b* and length *a* of the ellipse are considered as follows:

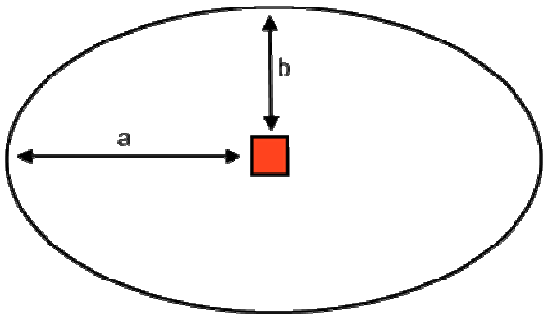


Figure 1. Elliptical heat influence area

The shape deformation of the ellipse by wind can be modeled through the calculation of parameters *a* and *b*:

- *b* is calculated through an exponential probability distribution function $b \sim \exp(\lambda_b)$, for $\lambda_b=1$ (*cf.* Figure 2.)
- *a* is initialized to *b* value plus a negative exponential law of parameter $a \sim b + \exp(\lambda_a)$ with $\lambda_a = \frac{3}{2} - 0.9\frac{\upsilon}{\upsilon_{\max}}$, where $\upsilon_{\max}$ is the maximum wind speed and υ is the wind speed, with $\lambda_a \in [0.6;1.5]$ (*cf.* Figure 2.) Therefore, the ellipse lengthens with wind strength. Under no wind conditions, it is highly probable that the ellipse will be a circle.

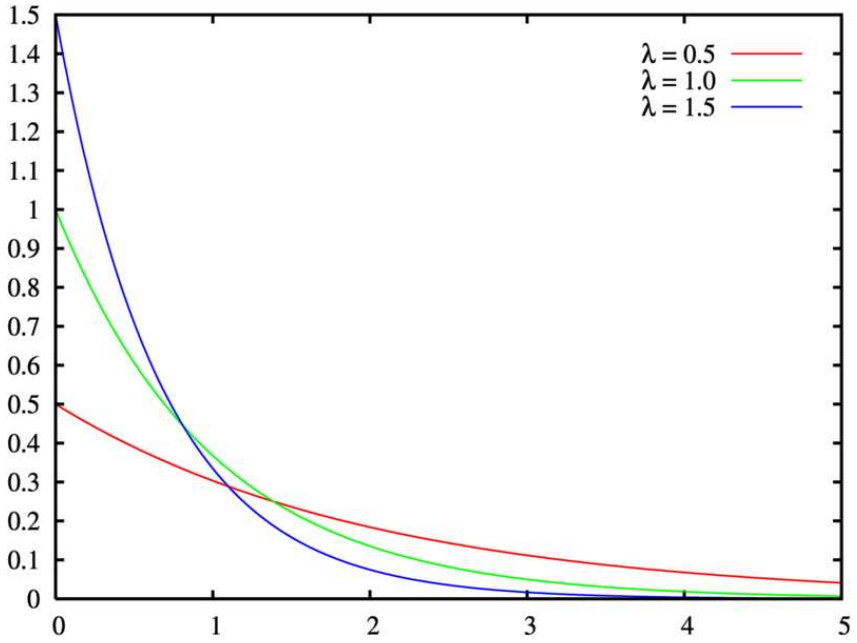


Figure 2. Density of probabilities of an exponential distribution

Then, once the ellipse shape is calculated, the ellipse is rotated according to wind direction, and translated according to wind strength:

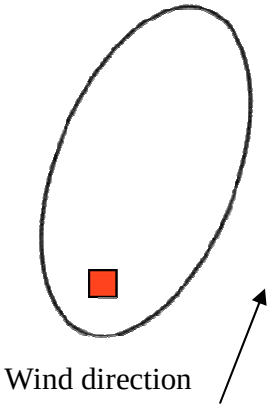


Figure 3. Ellipse rotated and translated

3.3 Heat influence: Physics-inspired and chemistry-based mathematical analogues

The conversion degree α represents the advancement of the reaction according to the temperature in the fuel. When $\alpha=100\%$, the reaction is over (all the combustible is burned.) When $\alpha>0\%$, the reaction starts. As experimentally proved in [42], $\alpha(T)$ is equivalent to a sigmoid function, depending on the gradient temperature β (*cf.* Figure 4.)

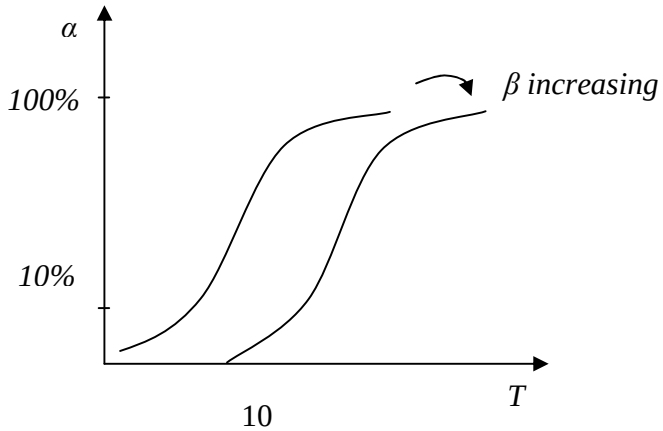


Figure 4. Simplified curve of conversion degree

If we refer to Equation (1), knowing the conversion degree α and the initial mass m_0, the current mass *m(t)* can be calculated. Therefore, the problem now is to determine the temperature propagation in space.

In the physics-based *point source model* [43] (*cf.* Figure 5), flames are modeled as point sources situated in the center of the flame. It is assumed that a fraction χ_r of the *total heat released rate* $\dot{Q}_i$, at position *i*, is received as a *thermal radiation flux* $\dot{\phi}_j$ by a target fuel (*T*), of dimensions A_j at position *j*. The radiated energy is calculated by dividing this fraction by the surface area of a sphere whose radius *r* is the distance from the middle of flame height to the influenced fuel.

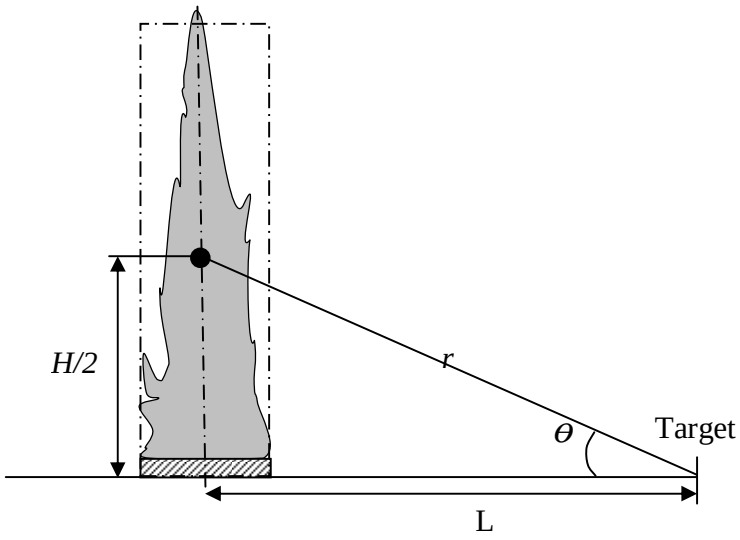


Figure 5. Geometry of radiation in the point source model

The *total heat released rate* $\dot{Q}_i$ is a product of the mass derivative in *i*, $\frac{dm_i}{dt}$ (*kg/s*), by the *heat of combustion* ΔH_i (*kJ/kg*), which is constant:

$$\dot{Q}_i = \frac{dm_i}{dt}\Delta H_i \tag{8}$$

Thus we obtain:

$$\dot{\phi}_j = \chi_r . \frac{dm_i}{dt} . \frac{\Delta H_i}{4\pi . r^2} . \cos(\theta) . A_j \tag{9}$$

Equation (8) remains valid for vertical flames, *i.e.*, without wind and/or slope. When the wind blows, the flame is inclined. Therefore, a relation needs to be found (*cf.* Figure 6 and reference [44] for more information), between: the angle formed by normal to the flame and the radiative ray directed to the target (φ_1); the angle formed by the normal to the fuel and the radiative ray directed to the target (φ_2); the distance between the emitter and the receiver; and the surface of emission and reception.

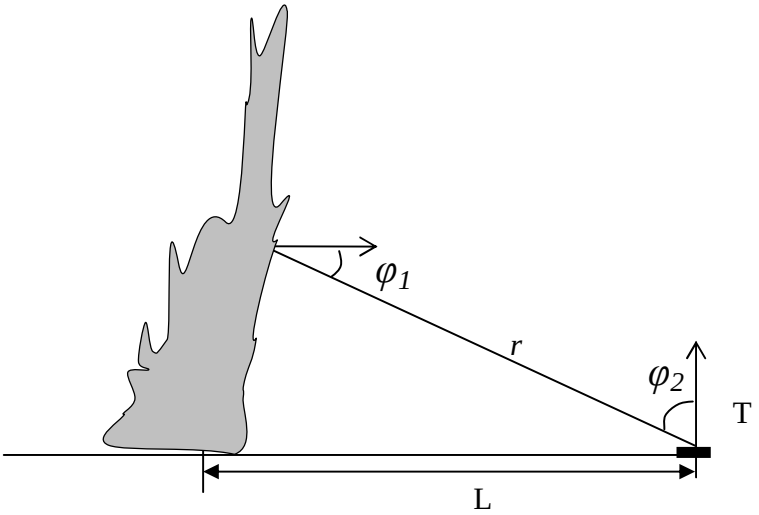


Figure 6. Geometry of radiation under wind

Using such a mathematical description of radiation geometry necessitates describing precisely the flame shape in three dimensions. Empirical formula can be used to determine the flame height (considered as constant) [45], such as:

$$H_i = 0.08\dot{Q}_i^{2/5} \quad (10)$$

Where $\dot{Q}_i$ is the rate of heat released at position *i*.

Then, wind conditions, using a precise modeling of gas motion, are integrated to determine flame tilt angle in the equation [46]. However, this *level of precision* is difficult (computationally possible?) to fit with actual gas and flame motion during a fire spread. Moreover, this requires manipulating physics-specific notions, which avoid proposing a simple propagation simulation model of fire spread. One solution is to use automata to build computational models of fire spread using mathematical analogues [47]. We attempt to go a step further here, building mathematical/computational analogues of physics-inspired processes of fire spread, integrating chemical processes.

We will take advantage of the *point source model* assumption, which considers that a portion of the total heat rate released by an ignited combustible is transmitted to the neighboring combustibles (without considering heat exchanges with air): $\chi_r \dot{Q}_i$. We assume now that a fraction χ_{h_i} of the total heat released at position *i* is transmitted (by radiation *and* diffusion) to the neighboring sites *j* and that this heat influence decreases with the square distance between the sites according to an exponential law (*cf.* Figure 7.) The precise geometry of the flame (and flame tilt) is not taken into account. χ_h is assumed to be proportional to the flame height: $\chi_{h_i} \propto H_i$ [*cf.* Eq. (10.)] Areas are considered to be equal at emission and reception (using a propagation cellular domain). We obtain the *heat influence rate* h_j:

$$\frac{dh_j}{dt} = \chi_{h_i} \dot{Q}_i e^{-qd^2} \quad (11)$$

Where q (m^{-2}) is a constant depending on fuel characteristics.

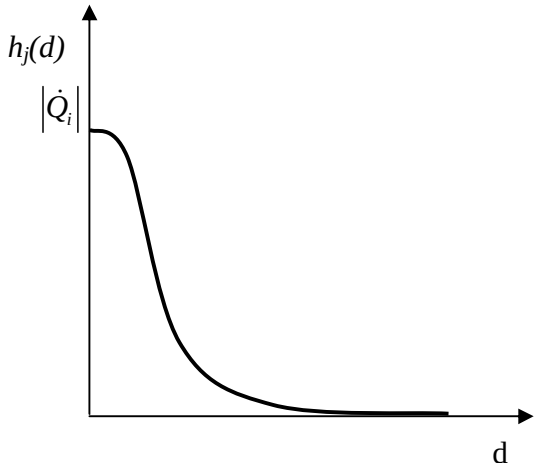


Figure 7. Heat influence as a function of distance

Considering a distance reduction factor $\delta_{ij} = e^{-qd^2}$ and combining Equation (8) with Equation (11), we obtain:

$$\frac{dh_j}{dt} = \chi_{h_i} \delta_{ij} \frac{dm_i}{dt} \Delta H_i \tag{12}$$

Now, another factor needs to be integrated for modeling heat transfers: Slope. We consider a slope reduction factor $\lambda_{ij} = z_j - z_i$, with z_i, the altitude at position *i*, and z_j, the altitude at position *j*. We obtain:

$$\frac{dh_j}{dt} = \chi_{h_i} \delta_{ij} \frac{dm_i}{dt} \Delta H_i (1 + \lambda_{ij}) \tag{13}$$

Another major parameter influencing a fire spreading is the moisture reduction of heat influence γ_j in the fuel. Moisture decreases the impact of heat on fuels. We obtain:

$$\frac{dh_j}{dt} = \chi_{h_i} \delta_{ij} \frac{dm_i}{dt} \Delta H_i (1-\gamma_j)(1+\lambda_{ij}) \tag{14}$$

The mass decrease in an ignited fuel [*cf.* Figure 4, Equation (3)] depends on the temperature in the fuel. Variations of the temperature in the fuel depend mainly on three causes: (i) the heat transfer received, (ii) the heat released, and (iii) the heat exchanged with the air. Causes (i) and (ii) increase the temperature in the ignited fuel. Cause (iii) decreases the temperature. Many equations can be written to model this temperature dynamics [46][44].

Previous equations have been developed for a one-dimension spreading considering two different sites in the fuel (one site ignited and influencing, the other one influenced.) In two dimensions, for many sites $\{i\}$ influencing one site *j*, we obtain:

$$\frac{dh_j}{dt} = (1-\gamma_j) \sum_{\{i\}} \chi_{h_i} \delta_{ij} \frac{dm_i}{dt} \Delta H_i (1+\lambda_{ij}) \tag{15}$$

Our aim here is not to reuse these equations. It is more to focus on the transfer and release of heat in fire spread and to combine both with the mass loss rate in combustible. Figure 8 sketches the temperature curve in fuels.

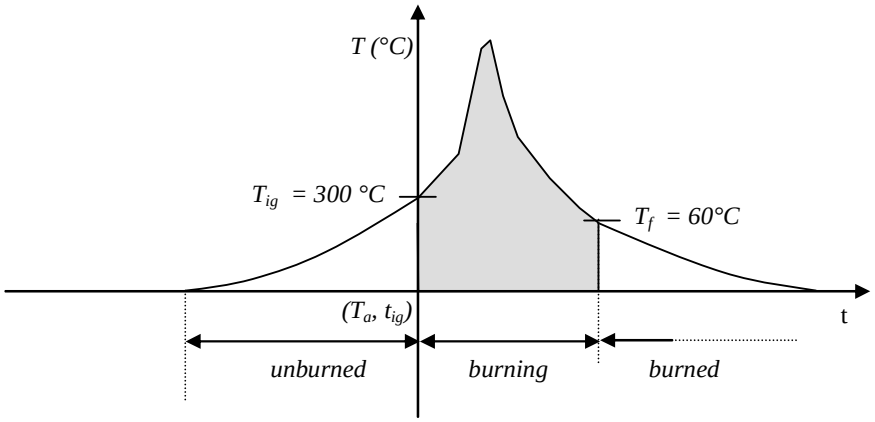


Figure 8. Simplified temperature curve of fuels

Therefore, we do not account explicitly for temperature cooling by the air and consider merely that the temperature in cell *j* is a proportion τ of the heat received in this fuel:

$$T_j \propto \tau h_j \tag{16}$$

Finally, we describe the simulation sequence by the following algorithm:

1. For all sites *j* influenced by ignited sites (an including them):
2. | Compute temperature: $T_j = \tau h_j$
3. For all ignited sites *i*:
4. | Compute mass loss: $\frac{d\alpha_i}{dT_i} = \frac{A}{\beta_i} e^{-E_a/RT_i} f(\alpha_i)$
5. | Compute total heat released rate at position *i*: $\dot{Q}_i = \frac{dm_i}{dt} \Delta H_i$
6. | Compute axis lengths of wind-based ellipse (area of heat influence of the ignited sites *i*):
   $\begin{cases} b \sim \exp(\lambda_b = 1) \\ a \sim b + \exp(\lambda_a) \end{cases}$, with $\lambda_a = \frac{3}{2} - 0.9\frac{\upsilon}{\upsilon_{\max}}$, where $\upsilon_{\max}$ is the maximum wind speed and υ the wind speed.
7. For all cells *j* influenced by ignited sites:
8. | Compute heat reception at position *j*: $\frac{dh_j}{dt} = (1-\gamma_j)\sum_{\{i\}} \chi_{h_i} \delta_{ij} \frac{dm_i}{dt} \Delta H_i (1+\lambda_{ij})$

Algorithm 1. Model computation sequence.

3.4 Fire brands

Fire brands (when occurring) have a major effect on a fire spread path. This phenomenon receives recent attention by physicists and computer scientists [48]. In [48], small world networks are used [49]. The travel distance of firebrands is calculated according to an exponentially decaying probability distribution depending on fuel type, moisture and wind.

Moisture influence has been previously integrated in last section. We consider here the wind influence on fire brands (through direction and travel distance.) According to the fuel type (*e.g.*, merely if it is a pine tree), a simple probability p_{fb} is used for fire brand occurrence (*cf.* Figure 9.)

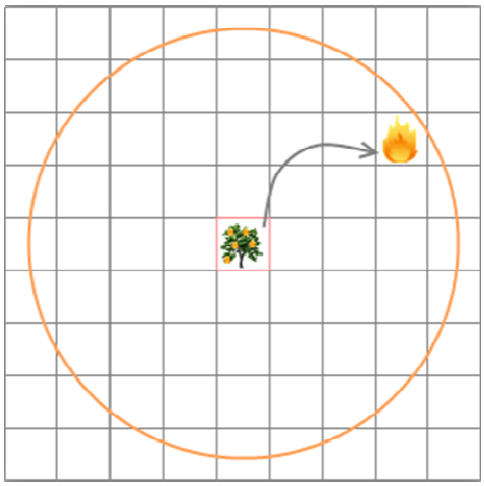


Figure 9. Fire brand ignition

If a fire brand occurs, the travel distance d_{fb} is determined according to an exponential law, based on wind speed v:

$$d_{fb} \sim \exp(\lambda_{d_{fb}} = \frac{1}{v}) \tag{17}$$

The emission angle ω is calculated according to a normal law:

$$\omega \sim N(\mu, \sigma^2) \tag{18}$$

With $\mu = v$ and $\sigma^2 = \frac{1}{d_{fb}}$.

Hence, the stronger the wind, the more chance has a fire brand to travel a long distance in the wind direction. Conversely, for low speed winds, fire brand distance is smaller and directions more stochastic.

4. Simulation results

We present here qualitative simulation results validating our modeling approach. First we check the temperature increase and decrease behavior presented in Figure 8. Colors are affected to temperatures. Figure 10 presents a fire spreading in a homogeneous fuel (green.) We can see that colors corresponding to temperatures change gradually from *brown* to *light yellow* and then back (during temperature decrease) to *brown* and finally *black.*

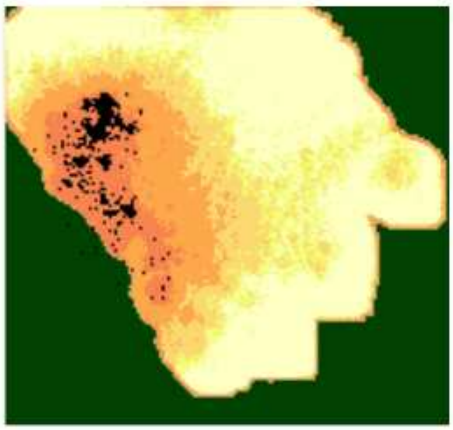


Figure 10. Temperature changes in the propagation domain

We then defined a simple image analysis filter for detecting vegetation species. Figure 11 depicts the original picture.

Figure 11. Original aerial picture of a possible propagation domain

Figure 12 describes a first image analysis of all the vegetation in the propagation domain.

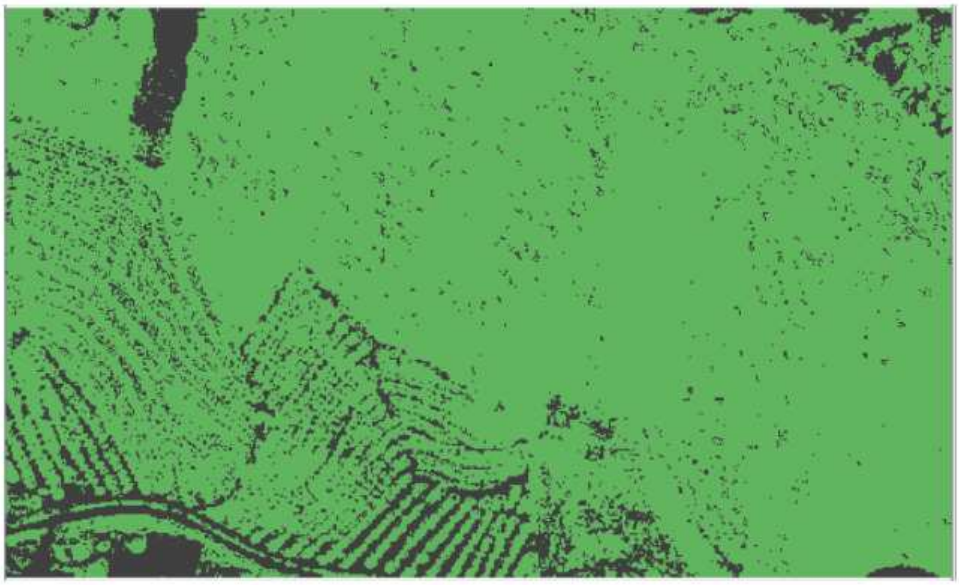


Figure 12. Detection of all the vegetation

Figure 13 depicts the detection of the shrub species (in light green.)

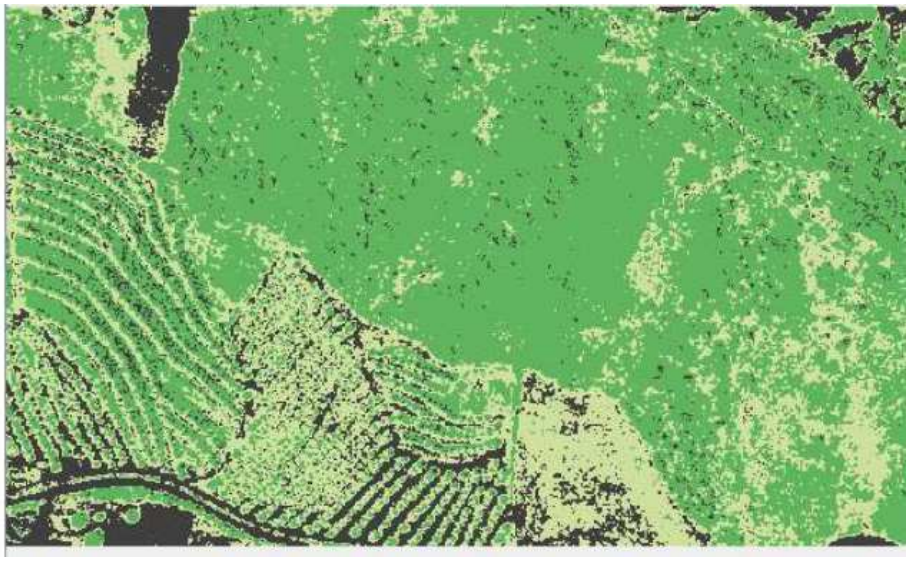


Figure 13. Detection of shrubs

Figure 14 validates the fire spread model under no wind, no moisture and no wind conditions.

(1)

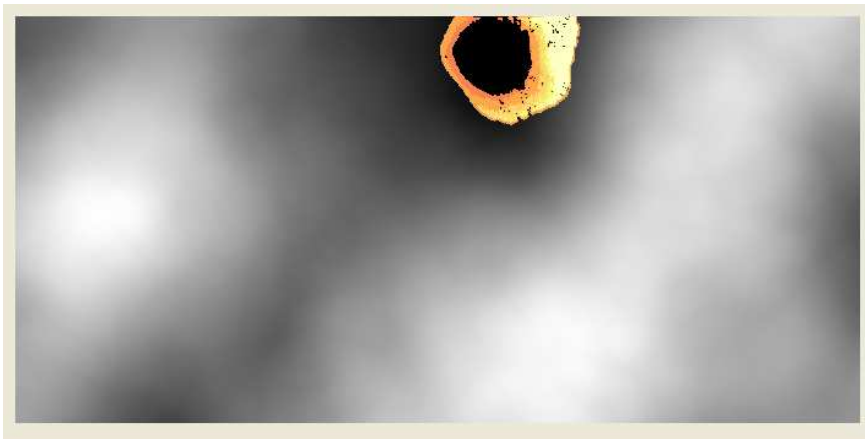
(2)

Figure 14. Fire spread simulation under no wind, no moisture and no slope. Fire spread is punctual and circular, except in areas without vegetation detected (*cf.* Figure 13.)

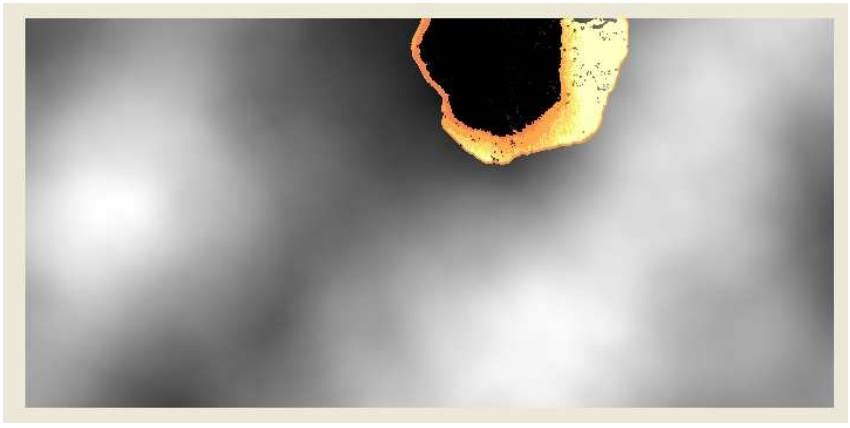
Figure 15 validates the fire spread model under no slope, no moisture and wind conditions.

Figure 15. Fire spread simulation under a wind of *50 Km/h* blowing west, no moisture and no slope. Fire spreads elliptically, except in areas without vegetation. Fire spread exhibits ignitions from fire brands.

Figure 16 validates the fire spread model under no wind, no moisture and slope conditions.



(1)



(2)

Figure 16. Fire spread simulation under no wind, no moisture and slope. Increasing slope, in the west direction, is indicated in black. Decreasing slope in the west direction is indicated in white. In (1), fire spreads first elliptically in the black area, regressing in the white area. In (2), fire spreads more in the black area and slows down in the white area.

Figure 17 validates the fire spread model under no wind, no slope and moisture conditions.

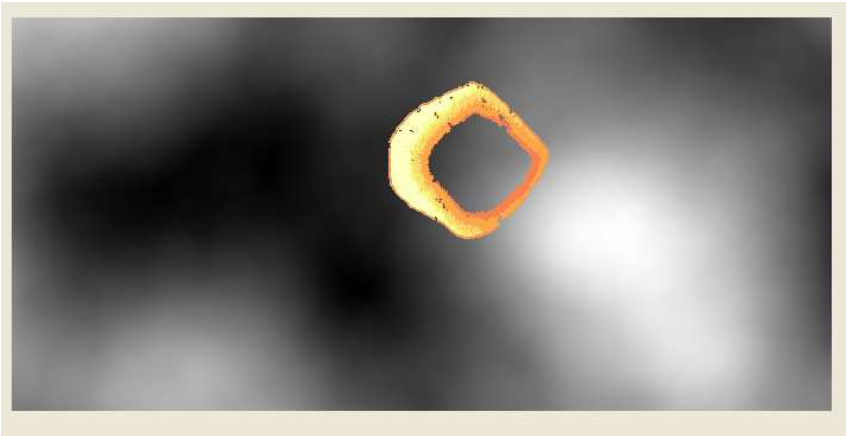


Figure 17. Fire spread simulation under no wind, no slope and moisture conditions. No moisture is indicated in black. Fire spreads more in the black area and slows down in the white area.

5. Discussion and perspectives

We have presented a chemistry-based, physics-inspired, computational model using mathematical analogues. Parameters of the model have been determined through virtual experiments, to achieve fire spread qualitative behaviors. As many fire spread phenomena have not been quantitatively described in physics, this global model tries to fill these modeling gaps. Mass loss of ignited fuel has been chosen as the major driving parameter of fire spread (through its impact on heat influence.)

Currently, only two simulation models incorporate physical rules and bi-dimensional propagation algorithms: [40][50]. Mathematical analogues and computational tools are fundamental to model and simulate fire spread. A lot of effort is necessary to develop mathematical and computational structures catching the main physical and chemical mechanisms of fire spread. The difficulty to achieve this goal resides in knowledge (and related vocabulary and models) which is specific to both chemistry and physics disciplines. However, fire spread can still be described at a first simple, rough, modeling level, using a *natural language vocabulary* for entities (wind, mass, heat released, heat influence...) and behaviors (spreading, brand sending, etc.) This kind of canonical model (and related vocabulary) can then be specified to particular domain-specific approaches (*e.g.*, “heat” will be called radiation, convection or diffusion in physics.)

We believe that a mathematical and computational framework can be developed through a non linear fire spread model integrating all interactions (heat with fuel characteristics, topography, climate, etc.), such as the one presented in Equation (15.) A long distance now remains to be covered for the experimental validation of all the reduction/interaction parameters of such an equation...

REFERENCES

[1] J.R. Curry et W.L. Fons, "Rate of spread of surface fires in the ponderosa pine type of California," *Journal of Agricultural Research*, vol. 57, 1938, p. 239–267.

[2] A.M. Grishin, "General mathematical model for forest fires and its applications," *Combustion, Explosion, and Shock Waves*, vol. 32, 1996, p. 503-519.

[3] R.H. McRae, "Use of digital terrain data for calculating fire rates of spread with the PREPLAN computer system," *Mathematical and Computer Modelling*, vol. 13, 1990, p. 37-48.

[4] D.H. Anderson, E.A. Catchpole, N.J. De Mestre, et T. Parkes, "Modelling the Spread of Grass Fires," *The ANZIAM Journal*, vol. 23, 1982, p. 451-466.

[5] J. Glasa et L. Halada, "On elliptical model for forest fire spread modeling and simulation," *Mathematics and Computers in Simulation*, vol. 78, Juin. 2008, p. 76-88.

[6] A. Alexandridis, D. Vakalis, C. Siettos, et G. Bafas, "A cellular automata model for forest fire spread prediction: The case of the wildfire that swept through Spetses Island in 1990," *Applied Mathematics and Computation*, vol. 204, 2008, p. 191 - 201.

[7] R. Lasaponara, "Editorial," *Ecological Modelling*, vol. 221, Jan. 2010, p. 1.

[8] E.J. Soltes, "Of Biomass, Pyrolysis and Liquids Therefrom," *Pyrolysis oils from biomass: producing, analyzing, and upgrading*, 1988, p. 1.

[9] S.S. Alves et J.L. Figueiredo, "Kinetics of cellulose pyrolysis modelled by three consecutive first-order reactions," *Journal of Analytical and Applied Pyrolysis*, vol. 17, 1989, p. 37–46.

[10] C. Di Blasi, C. Branca, et A. Galgano, "Thermal and catalytic decomposition of wood impregnated with sulfur-and phosphorus-containing ammonium salts," *Polymer Degradation and Stability*, vol. 93, 2008, p. 335–346.

[11] S.S. Sofer et O.R. Zaborsky, *Biomass conversion processes for energy and fuels*, New York, 1981.

[12] A.P. Dimitrakopoulos, "Thermogravimetric analysis of Mediterranean plant species," *Journal of Analytical and Applied Pyrolysis*, vol. 60, 2001, p. 123–130.

[13] R. Alén, E. Kuoppala, et P. Oesch, "Formation of the main degradation compound groups from wood and its components during pyrolysis," *Journal of Analytical and Applied Pyrolysis*, vol. 36, 1996, p. 137–148.

[14] J.H. Balbi, P.A. Santoni, et J.L. Dupuy, "Dynamic modelling of fire spread across a fuel bed," *Int. J. Wildland Fire*, vol. 9, 1998, p. 275–84.

[15] A.M. Grishin, "Mathematical modeling of forest fires and new methods of fighting them," *Translated by Czuma, M*, 1997.

[16] M. Statheropoulos, S. Liodakis, N. Tzamtzis, A. Pappa, et S. Kyriakou, "Thermal degradation of Pinus halepensis pine-needles using various analytical methods," *Journal of Analytical and Applied Pyrolysis*, vol. 43, 1997, p. 115–123.

[17] F.C. Beall, H.W. Eickner, et F.P.L.M. WIS, *THERMAL DEGRADATION OF WOOD COMPONENTS: A REVIEW OF THE LITERATURE.*, Forest Products Lab., Madison, WI, 1970.
[18] S. Liodakis, D. Bakirtzis, et A. Dimitrakopoulos, "Ignition characteristics of forest species in relation to thermal analysis data," *Thermochimica Acta*, vol. 390, 2002, p. 83–91.
[19] M.E. Brown, A.K. Kelly, et others, "A thermoanalytical study of the thermal decomposition of silver squarate," *Thermochimica Acta*, vol. 127, 1988, p. 139–158.
[20] T.P. Prasad, S.B. Kanungo, et H.S. Ray, "Non-isothermal kinetics: some merits and limitations," *Thermochimica Acta*, vol. 203, 1992, p. 503–514.
[21] T. Ozawa, "Thermal analysis–review and prospect," *Thermochimica Acta*, vol. 355, 2000, p. 35–42.
[22] S.V. Wight, "Isothermal and non-isothermal kinetics of thermally stimulated reactions of solids," *International Reviews in Physical Chemistry*, vol. 17, 1998, p. 407–433.
[23] S. Vyazovkin et C.A. Wight, "Model-free and model-fitting approaches to kinetic analysis of isothermal and nonisothermal data," *Thermochimica acta*, vol. 340, 1999, p. 53–68.
[24] A. Khawam et D.R. Flanagan, "Complementary use of model-free and modelistic methods in the analysis of solid-state kinetics," *J. Phys. Chem. B*, vol. 109, 2005, p. 10073–10080.
[25] T. Ozawa, "Thermal analysis–review and prospect," *Thermochimica Acta*, vol. 355, 2000, p. 35–42.
[26] J.H. Flynn, L.A. Wall, et A. Quick, "Direct method for the determination of activation energy from thermogravimetric data," *J. Polym. Sci*, vol. 4, 1966, p. 323–328.
[27] S. Vyazovkin et C.A. Wight, "Kinetics in solids," *Annual review of physical chemistry*, vol. 48, 1997, p. 125–149.
[28] T. Akahira et T. Sunose, "Joint convention of Four Electrical institutes," *Research Report Chiba Institute Technology*, vol. 246, 1971.
[29] H.E. Kissinger, "Reaction kinetics in differential thermal analysis," *Analytical chemistry*, vol. 29, 1957, p. 1702–1706.
[30] A.L. Sullivan, "Wildland surface fire spread modelling, 1990–2007. 3: Simulation and mathematical analogue models," *Int. J. Wildland Fire*, vol. 18, Juin. 2009, p. 387-403.
[31] R. Weber, "Modelling fire spread through fuel beds," *Progress in Energy and Combustion Science*, vol. 17, 1991, p. 67-82.
[32] A. Alexandridis, D. Vakalis, C. Siettos, et G. Bafas, "A cellular automata model for forest fire spread prediction: The case of the wildfire that swept through Spetses Island in 1990," *Applied Mathematics and Computation*, vol. 204, 2008, p. 191 - 201.
[33] I. Karafyllidis et A. Thanailakis, "A model for predicting forest fire spreading using cellular automata," *Ecological Modelling*, vol. 99, 1997, p. 87 - 97.
[34] S.G. Berjak et J.W. Hearne, "An improved cellular automaton model for simulating fire in a spatially heterogeneous Savanna system," *Ecological Modelling*, vol. 148, 2002, p. 133 - 151.
[35] L.H. Encinas, S.H. White, A.M.D. Rey, et G.R. Sánchez, "Modelling forest fire spread using hexagonal cellular automata," *Applied Mathematical Modelling*, vol. 31, 2007, p. 1213 - 1227.
[36] A.H. Encinas, L.H. Encinas, S.H. White, A.M.D. Rey, et G.R. Sánchez, "Simulation of forest fire fronts using cellular automata," *Advances in Engineering Software*, vol. 38, 2007, p. 372 - 378.
[37] G. Caldarelli, R. Frondoni, A. Gabrielli, M. Montuori, R. Retzlaff, et C. Ricotta, "Percolation in real Wildfires," *cond-mat/0108011*, Aoû. 2001.
[38] R.J. Mccormick, T.A. Br, et T.F.H. Allen, "T.F.H.: Towards a theory of meso-scale wildfire

modeling — a complex systems approach using artificial neural networks."
[39] A.L. Sullivan, "A review of wildland fire spread modelling, 1990-present, 1: Physical and quasi-physical models," *0706.3074*, Jun. 2007.
[40] B. Porterie, N. Zekri, J. Clerc, et J. Loraud, "Modeling forest fire spread and spotting process with small world networks," *Combustion and Flame*, vol. 149, 2007, p. 63 - 78.
[41] B. Porterie, S. Nicolas, J.L. Consalvi, J.C. Loraud, F. Giroud, et C. Picard, "Modeling thermal impact of wildland fires on structures in the urban interface. Part 1: radiative and convective components of flames representative of vegetation fires," *Numerical Heat Transfer, Part A: Applications*, vol. 47, 2005, p. 471–489.
[42] V. Leroy, D. Cancellieri, E. Leoni, et J.L. Rossi, "Kinetic study of forest fuels by TGA: Model-free kinetic approach for the prediction of phenomena," *Thermochimica Acta*, 2009.
[43] K.B. McGrattan, H.R. Baum, et A. Hamins, "Thermal radiation from large pool fires," *NISTIR-6546, NIST, Gaithersburg, Md., USA*, 2000.
[44] D. Drysdale, *An Introduction to Fire Dynamics, 2nd Edition*, Wiley, 1999.
[45] B.J. McCaffrey, "Purely buoyant diffusion flames: some experimental results," *National Bureau of Standards, NBSIR*, 1979, p. 79–1910.
[46] F. Morandini, P.A. Santoni, J.H. Balbi, J.M. Ventura, et J.M. Mendes-Lopes, "A two-dimensional model of fire spread across a fuel bed including wind combined with slope conditions," *International Journal of Wildland Fire*, vol. 11, 2002, p. 53–63.
[47] A. Dunn et G. Milne, "Modelling wildfire dynamics via interacting automata," *Cellular Automata*, p. 395–404.
[48] B. Porterie, N. Zekri, J. Clerc, et J. Loraud, "Modeling forest fire spread and spotting process with small world networks," *Combustion and Flame*, vol. 149, 2007, p. 63 - 78.
[49] D.J. Watts et S.H. Strogatz, "Collective dynamics of 'small-world'networks," *Nature*, vol. 393, 1998, p. 440–442.
[50] R.C. Rothermel, "A mathematical model for predicting fire spread in wildland fuels," *USDA Forest Service Research Paper INT (USA)*, 1972.