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Mathematical models and calculation systems for the study of wildland fire behaviour

E. Pastor, L. Zárate, E. Planas, J. Arnaldos*

Centre d'Estudis del Risc Tecnològic (CERTEC), Universitat Politècnica de Catalunya, Diagonal 647,
Catalonia, 08028 Barcelona, Spain

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Abstract

This is a review of the most important work in wildland fire mathematical modelling which has been carried out at different research centres around the world from the beginning of the 1940s to the present. A generic classification is proposed which allows wildland fire models to be sorted. Surface fire spread models, crown fire initiation and spread models, spotting and ground fire models are reviewed historically and the most significant ones are analysed in depth. The last two sections are dedicated to wildland fire behaviour calculation systems based on the reviewed models. The evolution and complexity of these systems is analysed in parallel with the development of new technologies. Special attention is given to the tools most commonly in current use by forestry agencies.

Keywords: Wildland fire; Surface fire; Crown fire; Ground fire; Spotting; Modelling; Simulation

Contents

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* Corresponding author. Tel.: +34-93-401-1733; fax: +34-93-401-7150.
E-mail address: arnaldos@eq.upc.es (J. Arnaldos).

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1. Introduction

Wildland fire mathematical models are generally composed of a collection of equations whose solution gives numerical values for the spatial/temporal evolution of one or more variables, such as rate of spread, flame height, ignition risk or fuel consumption. In this way, a more or less detailed description of system behaviour is obtained. Following this definition, wildland fire mathematical models may be classified.

According to the nature of the equations:

Theoretical models. Generated from the laws that govern fluid mechanics, combustion and heat transfer. Validation of these kinds of models is extremely difficult, although they may be extrapolated to a wide variety of fire situations.

Empirical models. Composed of statistical correlations extracted from experiments or historical wildland fire studies. These are only applicable to systems in which conditions are identical to those used in formulating and testing the models.

Semiempirical models. Proposed from simple, general and theoretical expressions, and completed through experimentation. Their extrapolation is adequate in situations similar to those used in obtaining experimental data. The difficulty in validating these models is less than in theoretical modelling, although it is significant.

According to the variables studied:

Wildland fire spread models. Provide the mechanisms for obtaining the main physical variables directly related to the fire perimeter advance. The most important variables, which the majority of the more complete models address are rate of spread, fire line intensity and fuel consumption.

Fire front properties models. Describe geometric flame features such as height, length, depth and angle of inclination.

According to the physical system modelled:

Surface fire models. The physical system is made up of surface fuel less than 2 m high. Small trees, bushes, herbaceous vegetation and fallen trunks are included.

Crown fire models. The physical system is formed by surface and aerial vegetation strata. If the fire front spreads burning both strata at the same time, an active crown fire is taking place. If fire consumes surface fuel and the crowns of individual trees it is defined as a passive crown fire.

Spotting models. The physical system is formed by firebrands or pieces of burning material which are transported by the convection column and carried beyond the main perimeter of the fire.

Ground fire models. The physical system covers the organic forest horizons below the litter which are formed by fermentation and humus layers that accumulate above mineral soil.

The combination of several wildland fire models and the use of computing tools to make calculations easier are essential mechanisms for forest fire management. Even if their use is not yet standard in Mediterranean Europe, they will be indispensable in forest management in the medium term.

Following this classification, the most relevant surface and crown fire spread models will be reviewed—theoretically, empirically and semiempirically as appropriate. After that, a brief description of spotting and ground fire models will be done. The reviewed models constitute the basic approach on which prevention and extinction decision support calculation systems rely. The last section will focus on these calculation systems.

2. Surface fire spread models

Surface fire spread modelling has been one of the most important tasks carried out in wildland fire research centres around the world in the last five decades. Several models—composed of a series of equations which relate environmental parameters to fire behaviour variables—have emerged from the activity over these years. Expressions for the rate of spread, fireline intensity and fuel consumption are obtained from physical fuel and landscape features, and from weather conditions. The importance of these kinds of models lies in the fact that present calculation systems are based on them. In Catchpole and De Mestre [1], Weber [2] and Perry [3] revisions of existing surface fire behaviour models that are classified as theoretical, empirical and semiempirical can be found. In Table 1 these models are summarised. In spite of the large number of models developed only few of them were used successfully in practical applications.

Surface fire spread modelling cannot be considered as definitely resolved with conclusive solutions, but it is one of the fields which has provided the most basic notions of wildland fire dynamics. Topographic slope and wind effects in fire spread heat transfer mechanisms and main fire

Table 1
Classification of surface fire spread models (1946–2000)

Reference	Type	Origin
Fons [4]	Theoretical	United States
Emmons [5]	Theoretical	United States
Hottel et al. [6]	Theoretical	United States
McArthur [7]	Empirical[a]	Australia
Van Wagner [8]	Theoretical	Canada
Thomas [9]	Theoretical	United Kingdom
McArthur [10]	Empirical[a]	Australia
Anderson [11]	Theoretical	United States
Frandsen [12]	Semiempirical	United States
Rothermel [13]	Semiempirical[a]	United States
Pagni and Peterson [14]	Theoretical	United States
Telisin [15]	Theoretical	Russia
Steward [16]	Theoretical	United States
Konev and Sukhinin [17]	Theoretical	Russia
Cekirge [18]	Theoretical	United States
Fujii et al. [19]	Theoretical	Japan
Grishin et al. [20]	Theoretical	Russia
Griffin and Allan [21]	Semiempirical	Australia
Huang and Xie [22]	Theoretical	United States
Sneeuwjagt and Peet [23]	Semiempirical	Australia
Albini [24,25]	Theoretical	United States
De Mestre et al. [26]	Theoretical	Australia
Weber [27]	Theoretical	Australia
Borrows et al. [28]	Semiempirical	Australia
Forestry Canada Fire Danger Group [29]	Empirical[a]	Canada
Croba et al. [30]	Theoretical	Greece
Marsden-Smedley and Catchpole [31]	Semiempirical	Australia
Grishin [32]	Theoretical	Russia
Dupuy [33]	Theoretical	France
Santoni and Balbi [34]	Theoretical	France
Linn [35]	Theoretical	United States
Catchpole et al. [36]	Semiempirical	Australia
Catchpole et al. [37]	Semiempirical	Australia
Fernandes [38]	Semiempirical	Portugal
Vega [39]	Semiempirical	Spain
McCaw [40]	Semiempirical	Australia
Viegas et al. [41]	Empirical	Portugal
Cheney et al. [42]	Empirical	Australia
Larini et al. [43]	Theoretical	France
Margerit and Guillaume [44]	Theoretical	France
Burrows [45,46]	Semiempirical	Australia
Hargrove et al. [47]	Empirical[a]	United States

[a] Models that constitute the basis of operating tools actually used in forestry agencies.

behaviour features are very significant parts of the knowledge that has been obtained from surface fire spread modelling.

2.1. Historical review

2.1.1. Theoretical models

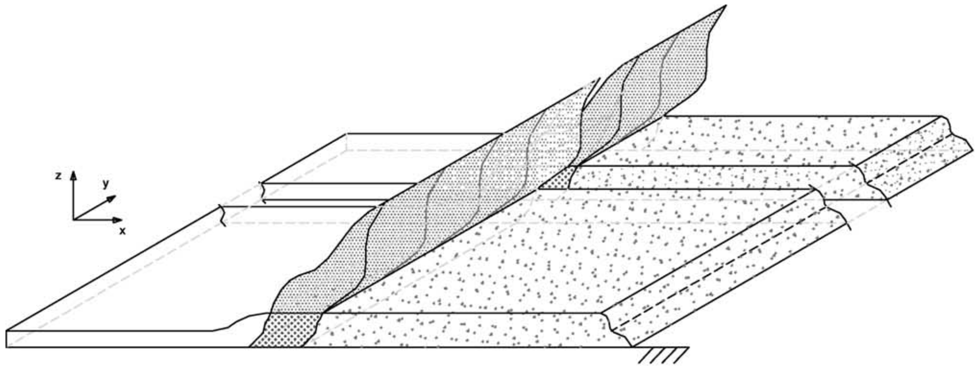
Attempts to develop theoretical models for surface fire behaviour have existed since the beginning of research in this area. They are based on the idealisation of fuel, fire line and flames in a simplified system in which mass, momentum and energy—conduction, convection and radiation—transfer equations can be applied to give a quantitative description of fire spread variables. The first model was developed by Fons [4] in the United States. It was a simplified example in which fire spread versus logarithmic growth of fuel bed temperature could be obtained by applying the energy conservation equation to a uniform volume of solid particles immersed in an ideal fire line. It was validated through laboratory experimentation on a continuous distribution of pine needles. The results were relatively good, despite errors in the model (Fons ignored the fourth power of temperature in radiation heat transfer equations). In spite of its shortcomings, Fons's model was the first essentially theoretical approach to modelling research.

A succession of theoretical models emerged between 1960 and 1990. Their approach to the description of the physical system was almost identical but they differed in the way theoretical principles were applied. Most of these models were built according to a one-dimensional, steady fire line spread hypothesis, which was represented by a combustion interface and a flat, rectangular, inclined isothermal fire front advancing across a homogeneous fuel bed. This fuel bed was characterized by its moisture content, its packing ratio and the surface area to volume ratio of its constituent particles, which were assumed to be uniformly distributed in all directions (Fig. 1).

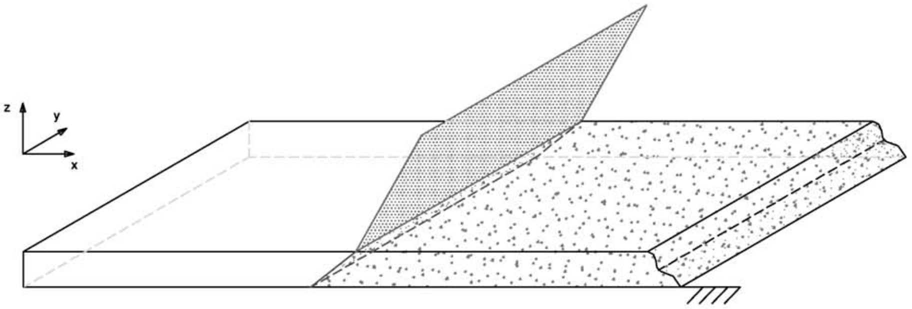
Nevertheless, several models differed from this initial approach. The Huang and Xie [22] and Albini [24,25] models incorporated fuel discretisation and fuel bidimensionality, respectively. Also, a temperature gradient inside the particles was considered in Thomas' [9] model. Cekirge [18], Fujii et al. [19] and Weber [27] suggested non-steady propagation; they tried to find a dynamic solution for fire line spread, but without much success.

The differentiating feature of the several existing models lies in the way the terms considered in the basic equations, with varying consideration of and dependence on different heat transfer mechanisms, and different determination of boundary conditions and control volumes. Almost all the authors took radiation as the dominant process in unburned fuel heat contribution. This term, however, received differing treatment according to the observed emission source (surface or volumetric depending on the consideration of flame or combustion zone), and the fuel characterisation (black or grey body as appropriate). An illustrative example is the work undertaken by Albini [24]. Most models generally treat the convective term in an unclear way. Except for the models by Pagni and Peterson [14] and Albini [25], heat contribution terms relating to hot gases present in the fuel bed were excluded from the results; gases were only qualitatively considered as an oxygen source for the combustion process.

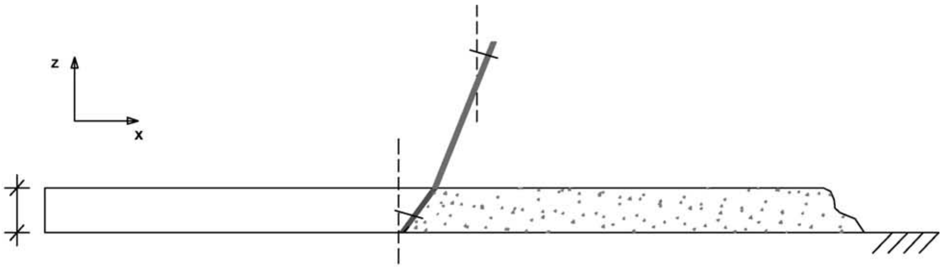
In spite of their differences, the result of all of these models was a set of differential equations whose boundary conditions were the ambient values of fuel temperature and



The surface fire front has infinite width and is moving forward in the x direction



Idealised surface fire front is represented by a flame and a combustion interface. They are flat, rectangular and inclined.



Final one-dimensional spread model

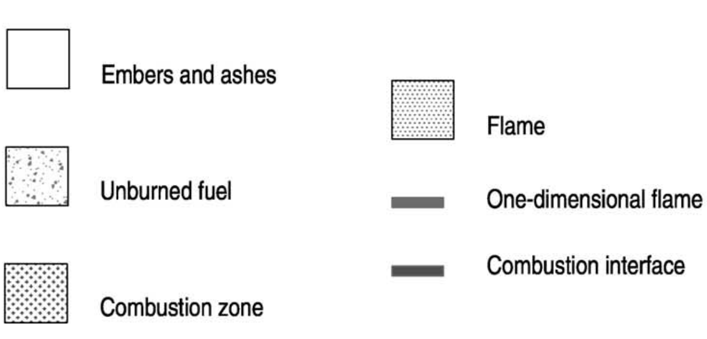


Fig. 1. Surface fire theoretical modelling. Physical system.

air temperature and velocity at the limit of the integration domain. Rate of spread was the numerical or analytical solution, according to the difficulty of resolution. Nevertheless, they were not free from empirical components which were indispensable to complete the models. Flame height and temperature could only be obtained from experimentation. Although scientific rigor was the goal, the results were not conclusive and consequently they were implemented pragmatically by forest fire managers. For this reason, and due to the continuing difficulty in evaluating the partial contribution of each heat transfer mechanism, empirical and semiempirical approaches to research arose. More accessible, approximate methods which did not attempt to provide knowledge of underlying fire dynamics were sought, with the aim of developing practical tools for day to day forest fire management.

2.1.2. Empirical and semiempirical models

Following Frandsen's work [12] in semiempirical surface fire modelling using global heat balances, Rothermel [13] created the most widespread and practical mathematical model to date. According to this author, the introduction of this model 'would permit the use of systems analysis techniques to be applied to land management problems' mainly regarding prevention work. Owing to its success in the majority of North American forestry management offices where it was implemented, an attempt was made to apply this model in Europe a short time later. The Rothermel work was developed under semiempirical lines and is therefore, reliant on the experimental conditions of testing. Its application to Mediterranean vegetation did not give success immediately, because of the difficulty of calibration process. However, it has been incorporated into complex wildland fire analysis tools that are applicable in Mediterranean Europe today.

Empirical modelling, which was developed along the same lines, had its precedent in the work by McArthur [7,10] in Australia. McArthur designed meters for determining the main surface fire parameters, which were developed by statistical correlations extracted from experimental burns. Later, Noble et al. [48] fitted equations to the meters. Nevertheless, the use of this model in landscapes with vegetation different from that of dry Eucalypt forest in Australia should be done with caution.

Empirical modelling research was also carried out in Canada. After observing more than 500 experimental fires, and with many wild fires documented, the Forestry Canada Fire Danger Group [29] designed the final version of a wildland fire behaviour prediction (FBP) model developed in the eighties. This model was applied with satisfactory results in Canadian forestry agencies, and became an essential tool for forest management.

2.1.3. New tendencies in theoretical modelling

Empirical and semiempirical tendencies in wildland fire modelling have given good results in the last two decades. However, the efforts to develop operational tools from theoretical modelling have not diminished. Although the basic physicochemical process which governs surface fire front spread is well known, a lot of chemical and thermodynamic questions related to fire behaviour are still to be resolved. In Mediterranean Europe, the United States, Canada and Australia, ambitious and innovative research programs have been started, with the aim of developing completely theoretical models which could predict all kinds of wildland fire behaviour, including surface fires. Grishin [32], Dupuy [33], Larini et al. [43] and Margerit and Sero-Guillaume [44], among others, are authors whose work follows this new theoretical modelling approach, characterised by a complex physical description of the system and broader and more detailed transfer equations (Table 2).

This research is subject to a series of limitations due to its current early stage of development. The problem lies in the unavoidable use of long and difficult calculations in order to resolve complex systems of equations, and in the inclusion of some little-known chemical and thermodynamic aspects. Dupuy [33] refers to the treatment of the key factors of turbulence and chemical reaction kinetics, two problems that will have to be resolved in parallel with wildland fire modelling in the future.

3. Crown fire models

Wildland fires that occur with crown combustion are extremely dangerous and very difficult to fight. Their modelling is very complex with regard to theoretical or empirical equations and the validation process, but it is strictly necessary in order to increase knowledge of large fire dynamics, and therefore, improve prevention and extinction work. Due to the complexity, few works have been published to date dealing with crown fires. They generally provide only a guide but are important enough to be analysed in detail.

Crown fire modelling depends on two basic questions: the analysis of surface to crown fire transition conditions, and the study of crown fire behaviour variables. Crown fire models may be thus classified as crown fire initiation models

Table 2
Features of new theoretical models

Feature	Description
Fuel description	Multiphase. Solid, liquid and gaseous phase
Spread hypothesis	Two-dimensional or three-dimensional and dynamic spread
Considered reactions	Vaporization, pyrolysis and combustion
Balances (for different phases)	Mass, chemical species, momentum and energy

Table 3
Classification of crown fire models (1957–2000)

Reference	Modelling	Type	Origin
Molchanov [49]	Initiation modelling	Semiempirical	Russia
Kilgore and Sando [50]	Initiation modelling	Empirical	United States
Van Wagner [51]	Initiation modelling	Semiempirical	Canada
Xanthopoulos [52]	Initiation modelling	Semiempirical	United States
Perminov [53]	Initiation modelling	Theoretical	Russia
Alexander [54]	Initiation modelling	Semiempirical	Australia
Kurbatskiy and Telitsin [55]	Spread modelling	Theoretical	Russia
Albini and Stocks [56]	Spread modelling	Theoretical	Canada
Van Wagner [57]	Spread modelling	Semiempirical	Canada
Rothermel [58]	Spread modelling	Empirical	United States
Albini [59]	Spread modelling	Theoretical	United States
Forestry Canada Fire Danger Group [29]	Initiation and spread modelling	Empirical	Canada
Finney [60]	Initiation and spread modelling	Semiempirical	United States
Grishin [32]	Initiation and spread modelling	Theoretical	Russia
Gomes da Cruz [61]	Initiation and spread modelling	Empirical	Canada
Scott and Reinhardt [62]	Initiation and spread modelling	Semiempirical	United States

and crown fire spread models. Table 3 shows the most important ones.

3.1. Historical review

The first published work on crown fires dates from the late fifties [49], but significant studies in this field did not appear until the seventies. Threshold numerical values for surface to crown fire transition were obtained by analysis of the main variables which determine this type of evolution: foliar moisture content, vertical continuity, wind velocity, fire line intensity, etc. The most relevant study of this period was the Van Wagner semiempirical model [51] which established fire line and rate of spread conditions for passive, active and independent of crown fire transition. Expressions developed by Van Wagner were well received and were later adopted by several authors, obviously without underestimating their limitations. The model starts from the Byram fire line intensity expression [63], which can be related to the energy flow rate in the convection column above a line of fire [64], but it does not take into account wind, slope or flame geometry effects. Nevertheless, the hypothesis proposed by this author constituted the starting point for most crown fire spread models.

3.1.1. Crown fire spread models

Research work on crown fire behaviour analysis started at the same time by studying influential parameters, such as wind velocity, crown bulk density, humidity, etc. The first models were developed in Canada by Van Wagner [57] and in the United States by Rothermel [58]. They were designed to give rate of spread, fire line intensity and crown fuel consumption and to be applicable in operation. Because of their empirical character, it is difficult to extrapolate them and they have clear limitations as regards reliability.

Van Wagner [57] developed a semiempirical procedure for obtaining the rate of spread of active and passive crown fire fronts in Canadian conifer plantations. He chose this kind of vegetation because of its clear stratification and its low fuel arrangement variability compared with naturally regenerated areas. The validation results were acceptable, and the model was immediately incorporated into North-American global prediction systems. In its later use in Mediterranean Europe, errors due to its application with different fuels should be considered or avoided by doing a correct calibration process.

Implementation of the Rothermel model [58] was in fact more critical. Rothermel obtained a statistical correlation for active crown fire rate of spread by observing and analysing eight large wildland fires in the Northern Rocky Mountains (western United States) between the sixties and the eighties. Using his surface fire prediction methodology modified by Albini [56], he estimated that active crown fire rate of spread was 3.34 times higher than that predicted with his surface fire model using fuel model 10 (timber, litter and understorey) and real environmental features. The results were underestimated owing to the use of surface fire analysis methodology [13,65]. Wind velocity and fuel characteristics in laboratory experiments carried out for surface fire model validation had different magnitudes for crown fires, which caused serious scale errors in application to large fires. Moreover, crown fire behaviour variables, such as crown height, bulk density and foliar moisture content, were not included. Lastly, the equations developed in Rothermel [58] had very bad standard deviations, which is another sign of poor precision predictions.

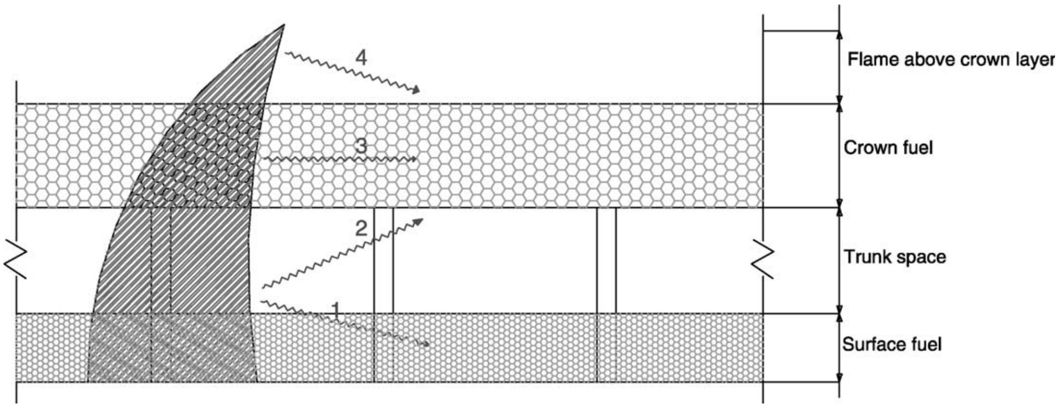


Fig. 2. Simplified representation of the radiation emitted from a crown fire front. (From Van Wagner [66].)

After this analysis it can be concluded that this model should be used with similar fires to those studied (in Rocky Mountain conifer plantations) with certain environmental conditions (wind speeds higher than 8 m s^{-1}, and slopes lower than 20%), though it has been incorrectly extrapolated to other situations and included in complex prediction systems.

Nevertheless, these methodologies were well received and integrated with surface fire modelling procedures. However, theoretical studies also had a huge impact, even if it was impossible to complete them and make them operational. A common feature in all this work was the consideration of radiation as the dominant heat transfer mechanism. The reference work concerning radiation is the Kurbatskiy and Telitsin model [55]. These authors correctly took into account both the flame radiation (understood as an external source) and the combustion zone radiation (in the aerial vegetation stratum understood as an internal source) (Fig. 2).

In the last decade there have been works in which crown fire initiation and crown FBP methodologies are proposed together. The most notable of these are the Grishin [32] model, due to its rigorous theoretical treatment, the Albini model [59], which was calibrated and tested in the most complex and documented experimental research program undertaken anywhere in the world (ICFME, The International Crown Fire Modelling Experiment, Alexander et al. [67]) and the models developed by the Forestry Canada Fire Danger Group [29] and by Finney [60], due to their integration in forest fire managements softwares. These last two works include the Van Wagner models [51,57], and Finney [60] incorporates the Rothermel [58] model. They are therefore, inevitably affected by all the previously described faults, which has to be taken into account in the assessment of results from wildland fire simulators in which they have been implemented.

4. Mathematical models for the study of spotting

Spotting is a phenomenon associated mainly to large wildland fires. It is very difficult to predict and it can create very dangerous situations to fire fighters, making their movements difficult and eventually has the potential to trap them between two fire fronts. In fires in the urban wildland interface spotting is reported as being a very dangerous source of ignition of fires in structures. Spotting also reduces the effectiveness of fire prevention, and makes the control of prescribed burns more complicated.

Despite the complexity and random nature of spotting, predicting the factors that lead to its occurrence and establishing the most likely places where it may occur help to minimise its effects.

4.1. Historical review

Unfortunately, there are few spotting models. Nevertheless, the results of a few of them have contributed valid information to our knowledge and our ability to predict the phenomenon. Numerical values for the distance at which spotting appears and the associated ignition probabilities are the main aims of spotting studies. The methodology used by authors for obtaining these results was theoretical in most cases, although statistical models based on historical analysis of large wildland fires have been found in bibliographic reviews (Table 4).

4.1.1. Theoretical models

Although the premiere experimental work on that subject, which is one of the most comprehensive researches on this field, was done by Tarifa et al. [68], the Albini works represents the first theoretical complete attempts, partially confirmed empirically, in the field of spot modelling. Albini gave expressions for the maximum distance of spotting initiation from the study of burning particle trajectories in

Table 4
Classification of spotting models (1967–2000)

Reference	Type	Origin
Tarifa et al. [68]	Semiempirical	United States
Muraszew and Fedele [69]	Empirical	United States
Albini [70]	Theoretical	United States
Albini [71]	Theoretical	United States
Albini [72]	Theoretical	United States
Ellis [73]	Theoretical	Australia
Woycheese et al. [74]	Theoretical	United States
Colin [75]	Empirical	France

a convective column emitted from passive crown fires [70], from burning piles of woody fuel [71] and from wind-driven surface fires [72]. The Albini methodology [70–72] is extracted from six mathematical submodels (Table 5). From these six submodels Albini proposes an expression for the maximum distance that a cylindrical particle with optimum diameter (considered as one which is still burning when it lands) can achieve. This particle is first lofted by a flame and then by a convection column, which is turbulent, steady and not affected by external air conditions, and is later transported by a wind field.

This methodology is strongly based on the study of drag forces and trajectories. However, experimental coefficients are integrated into the final expressions. The application of the model is strictly for obtaining maximum spotting distance; it never estimates ignition location probability. The simplifications adopted, such as the use of cylindrical particles and the assumption of a wind field with logarithmic distribution for vertical distances, but constant in time, are detrimental to its reliability in analysing real fires.

With regard to its practical application, the model is complemented by several spreadsheets, which are supported by graphics and figures. This makes obtaining an estimate of spotting distance according to fuel model and vegetation species easier. For this reason, the model has been easily integrated into several USDA Forest Service calculation systems [76–80].

Table 5
Submodels which make up the Albini model [70–72]

Submodels	Variables studied
Flame structure	Height, gas fluxes and dynamic pressure
Plume structure	Gas fluxes
Combustion of a cylindrical particle	Burning rate
Vertical trajectory of a cylindrical particle	Maximum height
Winds field structure on forestry cover	Velocity profiles
Horizontal trajectory of a particle	Maximum horizontal distance

Table 6
Submodels which make up the Woycheese et al.'s model [74]

Submodels	Variable of study
Flame–plume structure	Gas fluxes
Combustion of a spherical particle	Burning rate
Vertical trajectory of a spherical particle	Maximum height and maximum diameter
Horizontal trajectory of a particle	Maximum horizontal distance

Of the present theoretical studies, the most significant are the Ellis model [73], developed at the Commonwealth Scientific and Industrial Research Organisation (CSIRO-Australia), and the work which was recently carried out in the Department of Mechanical Engineering of the University of California by Woycheese et al. [74]. The latter is the most strict and precise spotting study which has been published to date. The authors obtain a final equation containing different variables relating to maximum spotting distance through independent modelling of several spotting aspects (Table 6). Although this model has not yet been adopted in a complex prediction tool with operational capacity, its clearly theoretical procedure allows acceptable reliability to be expected. This will allow it to adapt to any system. Its integration will involve two distinct modules: one for examining the wind velocity profile according to forestry cover, and one for considering the probability of spotting.

4.1.2. Empirical models

With the exception the Muraszew and Fedele [69] model, in which fire front production of embers (which are dragged by the convection column) in terms of their size is statistically studied, no other work has been found to date. At present, an empirical study of spotting in Mediterranean Europe [75] is being carried out at the CEMAGREF Research Institute (Aix-En-Provence, France), based on historical fires between 1994 and 1999. Physical fuel features which favour the occurrence of spotting are being analysed by laboratory experiments and a theoretical study is planned in the near future.

5. Ground fire models

The visual impact of ground fires is not as dramatic as that of surface or crown fires. Nevertheless, modelling this phenomenon is an indispensable task for the efficient protection of forest ecosystems. Ground fires are characterised by burning without flame and by spreading very slowly; however, they are very dangerous because they consume the organic layer of the soil and heat the inorganic layer tremendously, owing to the fact that they spread by direct contact with it [81]. These effects are very harmful to the forest's biotic activity, and unfortunately fire managers cannot predict them with sufficient accuracy.

Although the occurrence of ground fires is well documented [82–84], few experimental works that include the description of ignition, spread and heat transfer in ground fires have been conducted [85]. With regard to this research activity, two main subjects directly related to the gravity of the phenomenon have been studied. These are probability of ignition and heat transfer in ground fires.

5.1. Smouldering ignition models

Normally, a ground fire is started by the spread of a surface fire through litter and burning twigs, cones, surface roots and trunks. These types of fuel have greater residence times than fine fuels, which means that they become sources of sustained burning. If they are directly connected to the organic layers of the soil after the surface fire front has passed, a ground fire will start, provided that the conditions of the soil are those required for ignition.

Frandsen [86] and Hartford [87] have carried out the most important studies of these smouldering ignition limits. Using commercial, modified peat moss as a simulated fuel, they conducted a series of experimental tests in order to ascertain the relationship between theses limits and the moisture content, bulk density and ash content of the organic layer of the soil. Based on these studies, Frandsen [88] later developed a set of equations of smouldering ignition probability for different Alaska forest floor duff layers by testing real, organic soil samples.

Being able to predict sustained smouldering ignition is important to fire managers because it means that they can precisely estimate the effects and the danger of prescribed burnings, and the potential damage of ignition sources caused by humans or lightning. Canadian and American researchers have been working on two different research studies together, with the aim of developing a practical model of smouldering fire potential for use by fire managers in the boreal forest of Alaska and Western Canada [89]. The first is by Frandsen [88], as mentioned above, and the latter by Lawson and Dalrymple [90]. These authors have developed a set of equations that link moisture content at different soil depths in several types of boreal forest duffs to Duff Moisture Code (DMC) and Drought Code (DC) indexes[1] of the Canadian Forest Fire Weather Index (FWI) System [91], which are well known and widely used by fire managers.

5.2. Soil heating modelling

The smouldering combustion process of organic soils is not known with sufficient accuracy. Nevertheless, observations described by Artsybashev [92], Wein [84] and Ellery et al. [83] give a good drawing of the spread of a ground fire. Smouldering was viewed as a burning wave moving downward and laterally into porous unburned fuel, which creates a bowl- or balloon-shaped cavity whose geometry depends on soil combustion limits. Artsybashev [92] suggested that modelling this type of fire could be based on the idea developed by Fons [4] in his surface fire spread model, mentioned above.

Later, in a more accurate interpretation, Schneller and Frandsen [93] stated that an adequate model of the phenomenon should take into account the evolution of the heat flux and the thermal properties of the burning and the unburned zone. With reference to this idea, Frandsen [94] modelled the heat flux in a ground fire bearing in mind all the parameters on which it depends. This work constitutes a very important first step in achieving a model to completely describe heat transfer in ground fires and which will allow their effects to be better described.

6. Wildland fire calculation systems

The ultimate aim of wildland fire modelling, apart from increasing knowledge of wildland fire dynamics, is to create procedures that might be incorporated into calculation tools for the day-to-day work of forest fire managers. The evolution of this kind of tool has been closely linked to the development of different wildland FBP methodologies and to research in computer science and new technologies. Qualitative improvements in modelling results and advances in programming and in software design have been reflected in more powerful and versatile calculation systems, which have become more useful tools for land management.

6.1. Historical review

The appearance of effective wildland fire calculation systems used by different forestry agencies has been directly linked to the development of good mathematical models. The McArthur Grasslands and Forest Meters were the first tools which were used by forest fire managers. The meters appeared in the sixties thanks to Australian modelling led by McArthur [7,10]. They were a kind of slide rule composed of four concentric discs in which several variables, those included in the mathematical procedures, were represented. A grassland or forest fire front rate of spread was estimated by rotating the discs according to the actual values of the variables. These tools were well received, due to their ease of use and their degree of reliability. Improved versions of these tools are currently used nowadays.

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[1] The DMC is a numerical rating of the average moisture content of loosely compacted organic layers of moderate depth. This code gives an indication of fuel consumption in moderate duff layers and medium-size woody material. The DC is a numerical rating of the average moisture content of deep, compact, organic layers. This code is a useful indicator of seasonal drought effects on forest fuels, and amount of smouldering in deep duff layers and large logs.

6.1.1. Computer implementation of mathematical models

The gradual introduction of computers as work tools in the eighties prompted the appearance of wildland fire calculation software packages which used several mathematical models. The United States Department of Agriculture Forest Service was the pioneer in this field and developed the first version of the Behave program (FBP and fuel modelling system) in 1984 which was firstly programmed onto the TI-59 calculator [95]. It was based on the Rothermel [13] studies. Surface fire rate of spread and fireline intensity was given by this software, by inputting fuel and environmental data. In later versions the program has been improved with regard to its versatility (crown fire and spotting variables have been included) and with regard to its graphic user interface (data input and output have been made easier).

This program established a very important precedent for forestry agencies around the world. Similar tools, in which mathematical models from different origins were incorporated, were created in the nineties (Table 7). From Canada, procedures for surface and crown FBP were incorporated into the FBP system. In its updated version, FBP is compatible with the Windows operating system and calculates fire characteristics in Canadian fuel models. It was developed by Forestry Canada Fire Danger Group [29] and it is based on surface and crown fire empirical models on the Canadian Forest Fire Weather Index (FWI System). In Australia, the CSIRO (Commonwealth Scientific and Industrial Organisation) wildland fire research group did much the same with McArthur's work, by integrating it into the Csiro Fire Calculator, which is a simple guide application for quick wildland fire behaviour estimations. It is designed to replace old Australian meters. Lastly, new tools have come about in the United States which were based on the Behave system, with the aim of improving its shortcomings. The Nexus Microsoft Excel worksheet is a clear example [99] comprising a set of spreadsheets in which input and output tabular and graphic data interact providing a systematic, organised and simple methodology.

6.1.2. Integration of Geographical Information Systems for wildland fire simulation

Technological advances regarding the capture of cartographic information have led to the appearance of powerful programs for processing and managing landscape data. As in other disciplines, Geographical Information Systems have made a qualitative leap forward, which is especially notable for wildland fire studies. Together with other factors, digital representations of natural spaces have encouraged the development of complex FBP systems. Thus, forest fire managers can now bring a new approach to their work by adding the contribution of simple computer programs as compiled in Table 7.

This new vision is possible due to the fact that, apart from mathematical models for the prediction of fire characteristics, new wildland fire software packages incorporate numerical simulation techniques. These techniques allow users to work with GIS layers in which the fire front information is generated. The construction of wildland fire simulators may be split into two categories, those linked to a regular grid system and those linked to the continuous plane [101]. Following this classification, the most widely used techniques [102] are bond percolation and cellular automaton (regular grid) and elliptical wave propagation (continuous plane). They differ in how landscape is represented and in the criterion used to simulate fire growth:

- *Bond percolation simulation technique.* Landscape is represented by a lattice of square, triangular or hexagonal divisions as appropriate, and values of corresponding environmental features are incorporated into each division. Fire spreads from one box to its neighbours according to a specific probability of ignition and spread,

Table 7
Computer software for wildland fire calculation

Name	Reference	Main mathematical models[a]	Origin
Behave (FBP and fuel modelling system)	Burgan and Rothermel [96]; Andrews [78]; Andrews and Chase [97]	SFM Rothermel [13]; CFIM Van Wagner [51]; CFSM Rothermel [58]; SM Albini [70]	United States
FBP System	Forestry Canada Fire Danger Group [29]	SFM Forestry Canada Fire Danger Group [29]; CFSM Forestry Canada Fire Danger Group [29]	Canada
FireLab (problem solving environment)	Guarnieri et al. [98]	SFM Larini et al. [43]; SFM Dupuy [33]	European Union
Nexus (fire behaviour and hazard assessment system)	Scott [99]	SFM Rothermel [13]; CFIM Van Wagner [51]; CFSM Rothermel [58]	United States
Csiro fire calculator (fire danger and fire spread calculator)	CSIRO Bushfire Behaviour and Management Group [100]	SFM McArthur [7]; SFM McArthur [10]	Australia

[a] Regarding the most complete version. SFM: surface fire spread model; CFIM: crown fire initiation model; CFSM: crown fire spread model; SM: spotting model.

Table 8
Main features of simulation techniques

Features/techniques	Cellular propagation	Wave propagation
Landscape representation	Discrete (cells)	Continuous
Propagation criterion	Logical rules and probabilities	Mathematical functions
Calculation spead[a]	Lower	Greater
Programation complexity[a]	Lower	Greater
Precision[a]	Lower	Greater

[a] Values regarding these fields are comparatives between simulation techniques.

which is associated with each cell [103,104]. This probability is adjusted by an empirical fire behaviour mathematical model made using historical fire data.

- *Cellular automation simulation technique.* Fire advances equally on a landscape grid following a set of rules which determine the state of each cell, fire propagator or inhibiting [105]. These rules are based on theoretical and semiempirical mathematical fire behaviour models.
- *Elliptical wave propagation.* The fire front travels on a continuous landscape and draws a perimeter which is divided into a finite number of segments. Each vertex is considered as an ignition point of a small fire, which advances in an elliptical shape in homogeneous environmental conditions following the propagation criterion, established by an empirical, semiempirical or theoretical mathematical model. Therefore, the main fire front perimeter is the envelope of the small ellipses generated after a certain time interval. This simulation criterion is based on the wave propagation principle developed by Huygens [106].

The decision to choose cellular or wave propagation simulation techniques depends on the kind of the mathematical model which has to be simulated, and on technical criteria regarding precision, calculation speed and programming complexity [107]. The main features are shown in Table 8.

During recent years, a wide range of simulators including the technologies mentioned above have been developed at several research centres around the world (Table 9). The main components of most of them are mathematical models belonging to the Behave system,

Table 9
Computer softwares for wildland fire calculation that run with GIS

Name/origin	Reference	Main components[a]	
Dynafire, United States	Kalabokidis et al. [108]	SFM Rothermel [13]	Cellular simulation technique[b]
Cardin, Spain	Martínez Millán et al. [109]	SFM Rothermel [13]	Cellular simulation technique
Firemap, United States	Ball and Guertin [110]	SFM Rothermel [13]	Cellular simulation technique[b]
Wildfire, Canada	Wallace [111]	SFM Forestry Canada Fire Danger Group [29]	CFSM Forestry Canada Fire Danger Group [29]
Farsite, United States	Finney [60]	SFM Rothermel [13]; CFIM Finey [60]	SM Albini [70]; wave simulation technique
Burn, United States	Veach [112]	Rothermel [13]	Cellular simulation technique[b]
Sparks, Switzerland	Schöning [113]	SFM Rothermel [13]	Cellular simulation technique
SIIF Tragsatec, Spain	Álvarez [114]	SFM Rothermel [13]	Cellular simulation technique
Mefisto-Aiolos-F, Greece	Lymberopoulos et al. [115]	SFM Croba et al. [30]	Cellular simulation technique
Firegis, Portugal	Almeida et al. [116]	SFM Rothermel [12]	Cellular simulation technique[b]
Geofogo, Portugal	Vasconcelos et al. [117]	SFM Rothermel [13]	Cellular simulation technique
Firestation, Portugal	Lopes et al. [118]	SFM Rothermel [13]	Cellular simulation technique
Pfas, Canada	Anderson [119]	SFM Forestry Canada Fire Danger Group [29]	CFSM Forestry Canada Fire Danger Group [29]; cellular simulation technique
Pyrocart, New Zealand	Perry [120]	SFM Rothermel [13]	Cellular simulation technique
Prometheus, Canada	Canadian wildland fire growth model project team [121]	SFM Forestry Canada Fire Danger Group [29]	CFSM Forestry Canada Fire Danger Group [29]; wave simulation technique
Integrated Inflame Software System, European Union	Viegas [122]	Viegas et al. [41]; Marguerit and Guillaume [44]	Cellular simulation technique
Spread, Portugal	Mendes-Lopes et al. [123]	SFM Rothermel [13]	Cellular simulation technique[b]
SiroFire, Australia	Coleman and Sullivan [124]	SFM McArthur [7]; SFM McArthur [10]	Elliptical wave propagation
Embyr, United States	Hargrove et al. [47]	SFM Hargrove et al. [47]; Albini [70]	Cellular simulation technique[c]

SFM: surface fire spread model; CFIM: crown fire initiation model; CFSM: crown fire spread model; SM: spotting model.

[a] Regarding the most complete version.

[b] Cellullar automation.

[c] Bond percolation.

although there are considerable differences between them, such as the integration of procedures, the treatment of fire extinction and fire effects, and the inclusion of other methodologies for obtaining secondary fire behaviour parameters or meteorological variables.

The use of these systems as basic daily fire prevention and extinction tools has not been standardised in the majority of countries of origin, though Farsite [125] has been disseminated worldwide because it can be adapted to different kinds of vegetation (especially to the Mediterranean Basin) and because of its ease of use. This tool is suitable for carrying out complete and comparable analyses of different fire scenarios, because the simulation results are collected in ASCII, GRID-ASCII and GRASS-ASCII files in which the values relating to burned areas, burned perimeters, time of fire front arrival, fire line intensity, flame height, rate of spread and direction of main spread, heat per unit of area and crown fire activity are expressed in tabular and graphic form. Working with fire behaviour data on a real landscapes allows prevention and extinction strategies to be designed in a localised and individual way. However, Farsite has not been thoroughly validated. It is therefore, very difficult to detect the origin of inaccuracies, which may be due to data input or to mathematical modelling. The users of this software also have to spend a period of time carrying out the digital cartography before working with Farsite systematically. Finally, Farsite is not suitable for studying large forest fires due to the lack of a dynamic wind model on complex landscapes and the poor precision in crown fire models. However, Farsite can be considered one of the most useful tools for forest fire prevention and extinction decision-making.

7. Conclusions

Forest fire mathematical modelling, and especially surface fire modelling, is the main research activity aimed at improving and increase knowledge of fire dynamics, particularly through a theoretical approach. Nevertheless, empirical and semiempirical surface fire spread models developed by McArthur [7], Rothermel [13] and Forestry Canada Fire Danger Group [29] form the basis of complex fire prediction systems which are currently operating in Australia, the United States and Canada. These three examples have important differences with regard to fuel description and to the treatment of environmental parameters, but they are all based on empirical expressions. Although each one yields good results in managing the vegetation for which it was designed, unfortunately extrapolation to other fuel types is not easy.

With regard to crown fire modelling, the results of the mathematical models analysed are purely illustrative. Considerable improvements are needed to overcome this situation, and these must be based on a more theoretical treatment or on the elimination of the dependence on surface fire models, particularly on models developed in the laboratory.

Spotting models have contributed to our knowledge of the physical processes involved, such as plume and wind dynamics, combustion, drag forces, particle trajectories, etc. However, spotting is clearly a random phenomenon and the probabilistic processes necessary for obtaining good predictions are missing.

Several forest fire calculation operating systems have been developed in the United States, Canada and Australia. They have become more complex and versatile as new technologies have been developed and they work relatively well in the specific forestry types where they were designed. In order to adopt these systems correctly, an exhaustive evaluation process is needed, although this involves many difficulties: the practical implementation of a suitable experimental program, obtaining real fire data from the landscape to be managed, and the economic investment that this represents. These calculation systems are guides for supporting fire prevention and extinction decision-making, but they are not definitive tools. More research work must be done in order to improve them.

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