Wildland Fire Risk Maps using S²F²M*

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Abstract

Wildland fires are a critical natural hazard in many regions of the World. Every year, millions of hectares are burned in Tropical, Boreal and Mediterranean forest, which causes a wide variety of effects, from atmospheric emissions, to soil erosion, biodiversity loss and drainage alterations. Reduction of those negative effects of fire requires to improve current fire risk assessment methods. Wildland fire-risk assessment is a very significant issue. This risk assessment is usually based on ignition probability due to meteorological or human factors, but it does not usually consider propagation danger when a wildland fire has started. To evaluate propagation danger, it is necessary to apply some propagation model and simulate the behaviour of the fireline. However, this propagation danger must be evaluated considering many different possible scenarios. Therefore, the amount of simulations that must be carried out is enormous and it is necessary to apply high-performance computing techniques to make the methodology feasible. In this paper, a method for creating propagation danger maps based on factorial experimentation is described. The methodology was applied at a southern Europe scale during the 2004 summer season.

Keywords: Wildland fire, Propagation danger, Risk Maps, High-performance computing.

1. Introduction

Wildland fire is a very serious hazard that, every year, causes significant damage around the world from the ecological, social, economical and human point of view. These hazards are particularly dangerous when meteorological conditions are extreme with dry and hot seasons or strong wind.

For example, summer 2003 was very hot in the Mediterranean area and, in Portugal alone 420,000 hectares were burned and 20 people died. In October 2003, the strong wind caused a large fire in California that burned 300,000 hectares, destroying 3,361 houses and killing 26 people.

In this context, fire-risk maps become a very important tool for the authorities to prevent these accidents. However, most fire-risk mapping techniques evaluate the ignition danger based on meteorological conditions (temperature, humidity, rainfall, etc) and on human factors (negligence, arson, etc.), but do not take into account the propagation danger itself once a fire has been ignited. This feature is very important, because it can provide more complete information to determine the possible behaviour of a wildland fire and to determine those regions where an ignition is more dangerous by considering the possible rate of spread or flame intensity.

This danger depends on static factors such as the slope of the terrain or the vegetation type in that particular region, but also on certain dynamic factors such as the moisture content in the vegetation or wind conditions. It is not therefore possible to previously determine the actual conditions when a fire starts. As a result, it is not possible to evaluate beforehand the effective rate of spread or flame intensity in a real situation.

Several propagation models have been developed to predict fire behaviour [1;2;5;6]. These models require a set of input parameters, including vegetation type, moisture contents, wind conditions and so on, and provide the evolution of the fireline in simulation steps. However, in the case under

consideration, there is no set of input parameters to be applied to the propagation model because, as has been observed, it is not possible to know the value of each parameter when a fire starts.

Considering this uncertainty, our method to determine the possible rate of spread and flame intensity is based on statistical analysis. The method proposed takes the static parameters of the region under consideration (slope and fuel type) and applies statistical analysis by simulating the fire propagation, considering a wide range of parameter combinations to determine the average rate of spread and flame intensity in that particular region. This rate of spread and flame intensity represents the potential propagation danger for that region.

This methodology requires each region to be represented by an average slope and a dominant fuel type. The size of such cells cannot therefore be too large, so as to maintain a high degree of uniformity.

The methodology is promising, but it is not useful if only applied at a local scale: it must also be applied at a regional, national or even international scale (i.e. the Mediterranean region). Therefore, the whole region under consideration must be divided into a set of uniform areas, and the methodology must then be applied to all the areas within the region as a whole to provide a wildland-fire propagation danger map.

Our system, called S^2F^2M (Statistical System for Forest Fire Management) [3], does not feed the simulation core with "known'" single values, but carries out a set of simulations considering a range of possible values for those input parameters that are more uncertain.

The method implemented by our system requires considerable computation to reach a conclusion because a large number of simulations have to be run for each area, and a real map is composed of an enormous set of areas. To tackle this problem, we have used a parallel scheme (master-worker), implemented with an MPI [9] as a message-passing library and executed on a PC Linux cluster.

This paper is organized as follows: The factorial experimentation and basic concepts of the system are explained in section 2. The system's implementation is described in section 3. Section 4 sets out the results obtained, and finally, the main conclusions are reported in section 5.

2. Factorial Experimentation

This work has been undertaken using the concept of **designed experiments**. In this kind of experiment, it is possible to make deliberate changes in the controlled variables of a system or process. Results are observed and it is then possible to either make an inference or a decision about variables responsible for changes. When there are a number of significant factors involved (in our case, weather, wind speed,

slope, etc.), the best strategy is to use some kind of **factorial experiment**. A factorial experiment is one in which the factors vary at the same time [8] (for example, wind conditions, moisture content and fuel parameters). Each particular situation resulting from a combination of values is called a **scenario**.

In our specific case, each scenario represents a particular combination of input parameters, but it should be noted that the slope and fuel type are static features in our area of study. Therefore, the parameters that identify a particular scenario are the wind conditions and the moisture content of the vegetation.

For each scenario, it is possible to simulate the fire propagation, applying any propagation model, and to determine the rate of spread and the flame intensity for that scenario. This information represents the potential danger of that specific area in that particular scenario. The faster the propagation and the more intense the flame, the more dangerous the fire.

It should also be noted that there is no direct relation between rate of spread and flame intensity, because there are fuel types that present high propagation rate with low flame intensity, and vice versa.

The next step is to generalize this reasoning and apply it to some different scenarios. In this case, for a terrain representing a model of fuel with a certain slope, a different scenario represents the same terrain but with other combinations of moisture in the fuel.

Hence, we can focus our analysis on the procedure of generating possible scenarios.

2.1 Scenarios generation

Our system uses a wildland-fire simulator as a black box that needs to be fed with different parameters in order to work. A particular setting of the set of parameters defines an individual scenario. These parameters correspond to those proposed in the Rothermel model [10].

For each parameter, we define a rank and increment value, which are used to move throughout the interval. For a given parameter i (which we will refer to as *Parameter_i*), the associated interval and increment is expressed as:

$$[Inf\_threshold\_i, Sup\_threshold\_i], Increment\_i \qquad (1)$$

For each parameter i, it is thus possible to obtain a number C_i (parameter domain cardinality), which is calculated as follows:

$$C_i = \frac{((Sup\_threshold_i - Inf\_threshold_i) + Increment_i)}{Increment_i} \qquad (2)$$

Finally, from each parameter's cardinality, it is possible to calculate the total number of scenarios

obtained from the variations of all possible combinations.

$$\# Scenarios = \prod_{i=1}^{n} C_i \qquad (3)$$

where n is the number of parameters.

Once all the scenarios for a particular area (slope and fuel type) have been generated and the rate of spread and flame intensity have been evaluated for each scenario, it is then necessary to determine the general rate of spread and flame intensity for that area.

2.2 Rate of spread and flame intensity of a particular area

To determine the rate of spread and the flame intensity of an area, it is necessary to apply some form of statistical method, since we have a set of values corresponding to each scenario. One possibility would be to select the maximum value as being the value that represents the area under study. This approach would represent the most dangerous scenario, as the behaviour of that area and this approach is very restrictive, corresponding as it does to extreme situations that are not completely representative.

The average of these results is more feasible as the value representing the area.

3. Implementation

The concepts described above have been implemented in an operational system which incorporates a simulation kernel and applies the methodology for evaluating the average rate of spread and flame height throughout the possible terrain conditions (slope and fuel model). This system has been developed on a PC LINUX cluster using MPI as a message-passing library.

3.1 The simulation kernel

As a simulation kernel, S^2F^2M uses the wildland simulator proposed by Collin D. Bevins, which is based on the fireLib library [4]. **fireLib** is a library that encapsulates the BEHAVE fire behaviour algorithm [1]. In particular, this simulator uses a cell automata approach to evaluate fire spread. The terrain is divided into square cells and a neighbourhood relationship is used to evaluate whether a cell will be burnt and at what time the fire will reach the burnt cells.

As inputs, this simulator accepts maps of the terrain, vegetation characteristics, wind and the initial ignition map.

The output generated by the simulator consists of two maps of the terrain. In the first, each cell is labelled with its ignition time; in the second, each cell is labelled with its flame height. This

information must be used to calculate the rate of spread and an average from among all flame heights. To calculate the rate of spread, the distance between the ignition point and each particular cell in the terrain is divided by the ignition time of that particular cell. This calculation is repeated for each cell in the terrain to determine the maximum value of the rate of spread. This maximum value will be used as the rate of spread for that particular situation (Figure 1).

The flame intensity (height) for that terrain is calculated by evaluating the average flame intensity in the whole terrain.
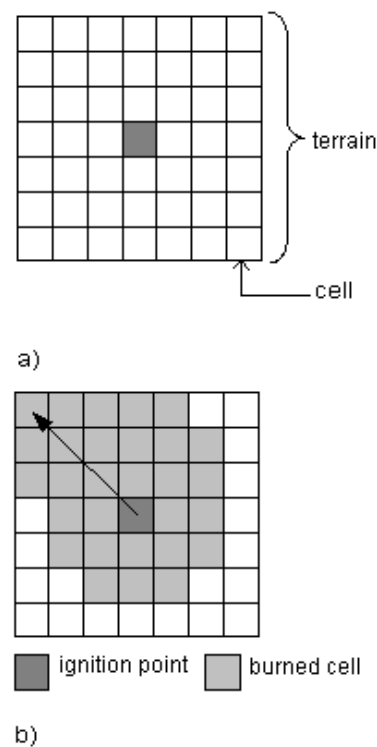

Figure 1: Methodology for calculating rate of spread. a) Ignition point in the middle; b) Search for maximal spread

To evaluate the rate of spread for a particular scenario (input parameter combination) in a given terrain, it is therefore necessary to simulate the fire propagation and then estimate the rate of spread and average flame height. This single calculation for a particular scenario is not very computer demanding and can be carried out on a single PC in a few seconds.

However, considerate should be recalled that the amount of scenarios to be evaluated for each terrain (slope and fuel type) is very large, as is the number of different terrains. Therefore, the total computation time required to estimate all the rates of spread is extremely large. The use of parallel/distributed

systems therefore appears as the only solution by which to make this approach feasible.

3.2 Parallel implementation

S^2F^2M has to make a large number of calculations given that it must make a simulation for each resulting combination of parameters (*#Scenarios*) and on each terrain. This high number of simulations requires considerable time.

To reduce execution time, we used multiple computational resources working in parallel to obtain the desired efficiency. Bearing in mind the nature of the problem that our system tries to solve, a master-worker architecture is suitable to achieve this aim (Figure 2). In this architecture, a main process (master) calculates all parameter combinations and sends them to a set of workers. These workers carry out the simulation corresponding to one of the scenarios and calculate the rate of spread and flame height, returning these results to the master.
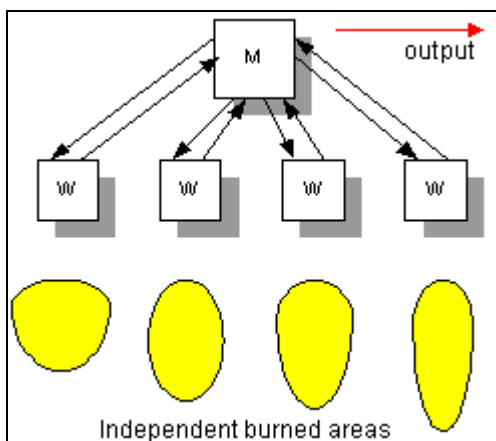

Figure 2: Conceptual example with four scenarios. M: Master process, W: Worker process.

Our system has a well-defined structure. The Master process has a data reception stage (parameter files, terrain files, simulation time, etc.). After this, there is an initialization stage for data structures. In the main loop, the Master process distributes scenarios to the workers, waits for results, receives results and distributes more data to idle workers (if there are more scenarios to simulate). Each scenario represents a combination of input parameters. When all the scenarios for a particular terrain have been calculated, the master process evaluates the average rate of spread and flame height for that particular scenario, and starts processing the new terrain. Finally, it provides a table listing the rate of spread and flame height for each terrain (*model, slope*) as output.

The Worker structure is complementary. Each one has a data-reception stage (to initialize terrain size, slope). Following this, it enters a loop to receive scenarios from the Master process. When the next scenario has been received, the worker activates the simulation function in order to calculate fire behaviour. Once the simulation has been completed, the worker evaluates the maximum rate of spread for that scenario, as well as average flame height. These results are sent to the master process, and the worker once more enters the reception stage.

4. Experimental results

Before tackling this problem, we used two experiments on tables and two experiments in the field to test the system, obtaining good results [3]. All of them were carried out in Portugal.

The experiments on tables were done using a device built specifically to this intention (Figure 3). This device is composed by a burn table of 3x3 m^2 that can be inclined at any desired angle (slope) and by a group of fans that can produce a horizontal flow above the table with an arbitrary velocity.

Figure 3: Burn table of 3x3 m^2

The burns in the field took place in Serra da Lousã (Gestosa, Portugal (40º 15'N, 8º 10'O)) , at an altitude of between 800 and 950 m above sea level. The burns were part of the SPREAD project [11]. In the Gestosa field experiments [7], terrain was divided into dedicated plots in order to carry out different sorts of tests and measurements (Figure 4).

In order to obtain a global view of risk associated to fuel loads, terrain characteristics and wind flows, a global simulation analysis was performed. This analysis tried to obtain average values of rate of spread and flame length, considering different wind and topographic conditions for the estimated fuel maps of the whole EUMed area. This attempt should be considered as a general overview of average expected fire behaviour at global scale, in order to

rank different danger levels according to the combination of fuel and terrain spatial patterns.

Figure 4: Image obtained during the burns

To provide the propagation danger map, we created a set of prototype plots, considering all the fuel models from Rothermel classification and a certain slope percentage (from 0 to 100%, with a step of 5%) (Figure 5).
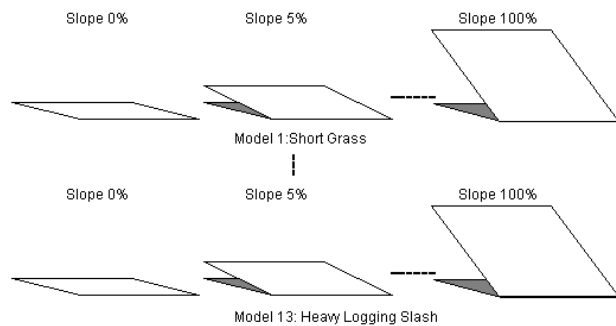

Figure 5: Synthetic Plot generation

The total number of plots was therefore 273. Each plot consists of a grid of cells with 11 columns x 11 rows (each cell measured 328.083 x 328.083 feet). The ignition point was located in the middle of plot. For each plot, many input parameter combinations were used to simulate the wildland fire behaviour and the average rate of spread and flame height were also calculated. The parameters considered for variation were: 1-hr dead fuel moisture, 10-hr dead fuel moisture, 100-hr dead fuel moisture, live herbaceous moisture. The ranges applied to these parameters and the precision considered were those established by Farsite Simulator [5]. These values are shown in Table 1.

Considering these ranges and precision steps, the number of simulations per plot was 4300, and the total number of simulations was 1,173,900.

For each independent result (scenario), a value of flame height is obtained as the average among the flame height for each cell. Then, in the final table, the value shown is the average for all different

resulting cases from combinations of moisture content. These values are shown in Figure 6.

Parameter	Inferior Threshold	Superior Threshold	Inc
1-hr dead fuel moisture	0.03	0.12	0.01
10-hr dead fuel moisture	0.04	0.13	0.01
100-hr dead fuel moisture	0.05	0.14	0.01
Live herb. Fuel moisture	0.7	1.7	0.3

Table 1: Parameter values

It can be observed that each model has a well-defined height rank, with a minimum and a maximum. However, it is interesting to observe that, in certain cases (for example, models 3 or 4), this is not completely linear or incremental according to the slope.
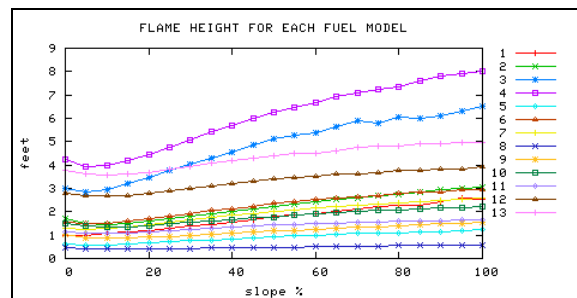

Figure 6: Flame height

On the other hand, each rate of spread found is averaged to calculate a representative value. These values are presented in Figure 7. In this diagram, we can see that the more inclined the terrain, the faster the propagation. Therefore, the more dangerous the fire.
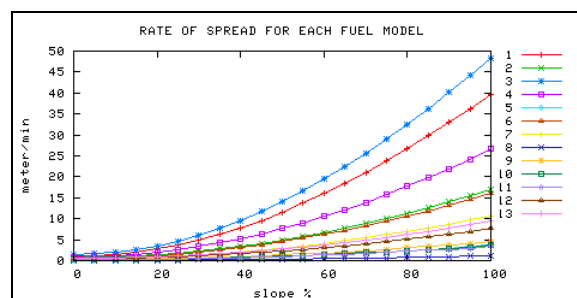

Figure 7: Rate of spread

Observing the two figures at the same time, it is possible to conclude that flame height has no direct relation to rate of spread. For example, model 1 has a high rate of spread on a high slope, but its average flame height is not particularly great. This behaviour must be taken into account to avoid erroneous

conclusions: in a wildland fire, this could be very dangerous.

These results can be applied to a European scale. To do so requires a European map divided into cells that include the average slope and dominant fuel model for each cell.

When the European maps are available, it is possible to elaborate two different maps from these: one for rate of spread-propagation danger and one for flame-height propagation danger. These maps are shown in Figure 8 and Figure 9.
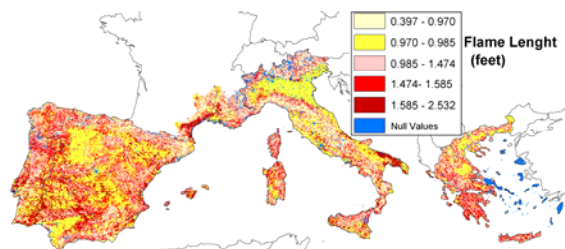

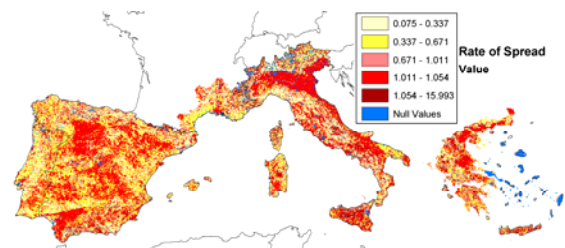Figure 8: Flame-height propagation danger Map of the EUMed

Figure 9: Rate of spread-propagation danger Map of the EUMed

5. Conclusions

In this paper, we have described our use of a tool called S^2F^2M with the objective of building a Wildland-Fire Propagation Danger Map for southern Europe. The propagation Danger is estimated on the basis of two different propagation features: rate of spread and the flame height. The calculation of the propagation danger is based on a factorial experimentation in which all possible parameter combinations are simulated and the results are averaged. This calculation requires a very considerable amount of simulation and it is therefore necessary to apply parallelisation techniques to elaborate the propagation-danger map within a reasonable time. The parallelisation was carried out by applying a master /worker scheme.

The application of parallel processing opens new possibilities for the applicability of the methodology to a real-time wildland fire assessment environment.

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