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Simulating the Wildfire in Rhodes in 2008 with a Cellular Automata Model

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We demonstrate how a cellular automata modelling approach offers a suitable method to develop a real time simulator able to describe the evolution of a fire front on higlhy heterogeneous landscapes. Importantly, we show that, differently from other approaches like CFD simulations in the continuum, a micro-simulator based on a cellular automata can be used for real-time and mutil-time assessement as the computational time that takes to run a compete simulation is of orders of magnitude shorter than the time period during which a real fire incident develops. The model takes into account factors such as the type and density of vegetation, the wind speed and direction and the spotting phenomenon. The model is used to simulate the wildfire that destroyed part of Rhodes in July of 2008. The model parameters have not been adjusted to fit the real incident; they have been kept at the values used to simulate other large-scale wild fires such as the fires of Parnitha in 2008 (Alexandridis et al., 20011) and the fire in Spetses in 1990 (Alexandridis et al., 2008). The comparison between the simulation and the real data obtained from Geographical Information Systems (GIS) showed that the model predicts efficiently the spatio-temporal evolution of the real incident and as such could be potentially used to develop a risk-management tool for controlling and assess wildland forest fires in heterogeneous landscapes.

1. Introduction

The increase of the incidence of wild-forest fires is among other important factors one of the devastating consequences of the climate change (Bergeron and Flanningan, 1995). Forests are entire ecosystems often hosting rare-animal and plant life and hence their destruction leads to wide-range serious ecological damages. Moreover, rural properties, villages and civil infrastructures lying in the vicinity of forests have also suffered from the ravages of wildfires which threaten -and result to the loss of- human lives. More than 50.000 forest fires larger than one hectare erupt each year, with an annual average of 500000 hectares of burnt forests in European Union, most of them located in South European countries. During the summers of 2007 and 2008, Greece experienced the worst damages over the last 100 years. One of the biggest fires in the summer of 2008 was the one that broke up in Rhodes Island: a total of 13000 ha of burnt area, from which 10000 ha were not formerly burnt, 2000 ha double burnt (formely reforested) and 1000 ha was agricultural area. The disastrous fire caused huge ecological damage and it was estimated that it will take as many as 30 to 40 years before the forest is restored. The total fire fighting force worked for five to six days with 1230 fire fighters, 1000 people from Greek armed forced, 200 volunteers, 75 fire fighting vehicle, 46 other vehicles, 10 aircrafts and 9 helicopters. The total suppression cost was estimated about 16 million €. Turning one year back in time the death toll in Greece due to the wild-fires was more than 75 people. There is no doubt that that the need for designing and developing effective ways of combating forest wildfires becomes one of the most challenging and important problems of our times. Towards this aim computer simulations play an important role in both preventive and operational tasks. Such simulations usually take into account both environmental factors like meteorological conditions and specific characteristics of the landscape like type of vegetation and density. According to Fons (1946), the

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most important factors that affect the rate of spread and shape of a forest fire front are the fuel type, humidity, wind field, forest topography, fuel continuity and volume and spotting.

Building a mathematical model that could predict the spread of a wildfire, taking into account all the aforementioned factors is not an easy task as between them there are complex interactions, often poorly understood (Albini and Brown, 1996). Moreover, the physical and chemical processes which characterize the evolution of the fire stress among different spatio-temporal scales. After the pioneering work of Rothermel (1972), the subject has been further developed resulting to many models. In particular, Rothermel has identified the dynamic equations that characterize the maximum fire spread rate based on laboratory experiments. Rothermel's equations have subsequently been applied in a variety of approaches which in terms of spatial representation can be categorized in two types. The first type consists of models in the continuum, where it is assumed that the fire-front travels on a continuous (homogeneous) landscape, forming an elliptical pattern. Solutions to these models are usually obtained by solving a system of partial differential equations which however they are computationally demanding (Richards, 1995). The second type, which is simpler and computationally faster, consists of the models that are based on a micro-scale simulation on grids (Pastor et al 2003). Among them, models based on the Cellular Automata (CA) methodology appear very promising especially for real time computations (Sullivan, 2009; (Karafyllidis and Thanailakis 1997; Alexandridis et al. 2008, 2011a, b). More specifically, the macroscopic space scale is described with a finite grid divided into a large number of cells. Each cell is usually characterized by several key discrete-state variables evolving in discrete time.

The evolution is regulated by a set of Markovian –Monte Carlo rules and depends, in general, just on the states of the neighboring cells, although more complicated rules may include long-range dependence and memory in time. CA has proven to be particularly powerful in predicting emergent complex macroscopic dynamics from simple rules defining the physics at the microscopic-atomistic scale (Von Neumann, 1966). Furthermore, such detailed grid models can easily incorporate digital data from Geographical Information Systems (GIS) or other sources (like data from weather stations).

This work presents the results of the simulation for predicting the spread of a wildfire that swept through Rhodes in July of 2008. Importantly we show that the proposed detailed model is robust enough as it predicted in a quite adequate manner the evolution of the real incident without fine-tuning its parameters. These were kept constant at the values estimated from other large-scale wildland fire incidents in previous studies (Alexandridis et al. 2008, 2011a, b).

2. The Cellular automata model for the fire propagation.

Here we present very briefly the proposed CA model (the interested reader can refer to Alexandridis et al., 2008, 2011). The model uses a two dimensional grid splitting the area into a number of cells. Each cell represents a small patch and its shape has been chosen to be square, thus offering eight possible directions of fire spreading. It should be noted that more complicated polygons, like hexagons, may be chosen to account more directions (Triunfo, 2004).

A finite number of states characterize the evolution in time of each cell. We consider for each cell 4 possible states which are defined as following:

STATE 1: The state of a cell is one, when there is no forest fuel. This state may describe the cells that contain sea, parts of the city with no vegetation, rural areas with no vegetation etc.

STATE 2: The state of a cell is two, when the cell contains forest fuel that has not ignited.

STATE 3: The state of a cell is three, when the cell contains forest fuel that is burning.

STATE 4: The state of a cell becomes four, when the contained fuel has been burned down.

The evolution in time of each cell is characterized by a set of rules which define if at each time if the state of the cell should be changed or not. In summary, starting from an initial condition, which assign a specific state at each cell, at each discrete time step t of the simulation, the following rules are applied to the elements i, j of the grid:

Rule #1: IF state (i, j, t) = 1 THEN state (i, j, t+1) = 1

This rule implies that the state of a cell with no forest fuel (empty cell) remains in the same state and thus it cannot catch fire.

Rule #2: IF state (i, j, t) = 4 THEN state (i, j, t+1) = 4

This rule implies that the state of an empty cell that has been burned down in the previous step stays in the same state.

Rule #3: IF state (i, j, t) = 3 THEN state (i, j, t+1) = 4

This rule implies that a burning cell at the current time step will be burned down at the next time step.

Rule #4: IF state (i, j, t) = 3 THEN state (i±1, j±1, t+1) = 3 with a probability p_{burn}

This rule implies that if a cell which is burning at the current time step then the neighbouring cells at the next time step will catch the fire with a probability p_{burn}.
This probability is a function of various parameters and it is calculated using the flowing formula:

$$p_{burn} = p_h(1+p_{veg})(1+p_{den})p_w p_s \tag{1}$$

where p_h denotes the constant probability that a cell adjacent to a burning cell containing a given type of vegetation and density will catch fire at the next time step under no wind and flat landscapes. The probabilities p_{veg} and p_{den} represent the effects of the type and density of vegetation, respectively. More specifically the type and the density of vegetation in the area are split into a number of discrete categories.
The effect of the wind is captured from the probability p_{w} which is calculated from an a empirical wind-effect relation that contains the effect of wind velocity and direction as computed by the following equations:

$$p_w = \boldsymbol{exp}(c_1 V) f_t \, ; f_t = \boldsymbol{exp}(V c_2 (\cos(\theta) - 1)) \tag{2}$$

where c_1, c_2 are constants to be determined and θ is the angle between the direction of the fire propagation and the direction of the wind.
The effect of ground elevation (slope) is modeled using the following equation, introduced in [22]:

$$p_s = \boldsymbol{exp}(a\theta_s) \tag{3}$$

where θ_s is the slope angle of the patch and a is a constant that can be adjusted from experimental data.
It should be noted that due to the square grid, the slope angle is calculated in a different way depending on whether the two neighboring cells are adjacent or diagonal to the burning cell. More specifically for adjacent cells the slope angle reads:

$$\theta_s = \boldsymbol{tan}^{-1}\left(\frac{E_1 - E_2}{l}\right) \tag{4}$$

where E_1 and E_2 are the altitude of the two cells and l is the length of the square side, whereas for diagonal cells the formula becomes:

$$\theta_s = \boldsymbol{tan}^{-1}\left(\frac{E_1 - E_2}{l\sqrt{2}}\right) \tag{5}$$

Notice that these probabilities are multiplied by the constant probability p_h to give the corrected probability that takes into account all the aforementioned factors (for a detailed discussion about the above parameters, please refer to Alexandridis et al. 2011a).

3. The Case Study and Simulation Results

We applied the proposed methodology to predict the spread of a real fire that devastated Rhodes in July 2008. The forest fire of Rhodes occurred on 22.08.2008 and broke out at 11.40 am at the location named Ag. Isidoros of the Municipality of Attaviros. The disastrous fire caused huge ecological hazards like the incineration of thousands of Pinus brutia that was among the dominant species of trees in the region. The cause of the fire was identified as negligence. The wind was W-NW-4-5 bf at the time of the eruption. The consequences of the fire were 13,240 ha of burnt area. The fire burned also houses and a great number of cultivated areas, machinery, equipment and also many animals. Firefighting lasted for more than five days. It involved 1.230 fire fighters from the Fire Brigade Service, 1.000 people from the Greek army, 200 volunteers, 75 fire fighting vehicles, 46 other vehicles, 10 aircrafts and 9 helicopters**.** The total suppression cost was estimated at the level of 16millon €.
A Satellite image of the burned area is reported in figure 1. Before applying our proposed model we generated the states of the altitude, vegetation density and vegetation type matrices based on digital

geographical data. For this purpose, we used Arc GIS 9.2 by ESRI. The digitalization of photomaps that were taken before and after the wildfire incident.

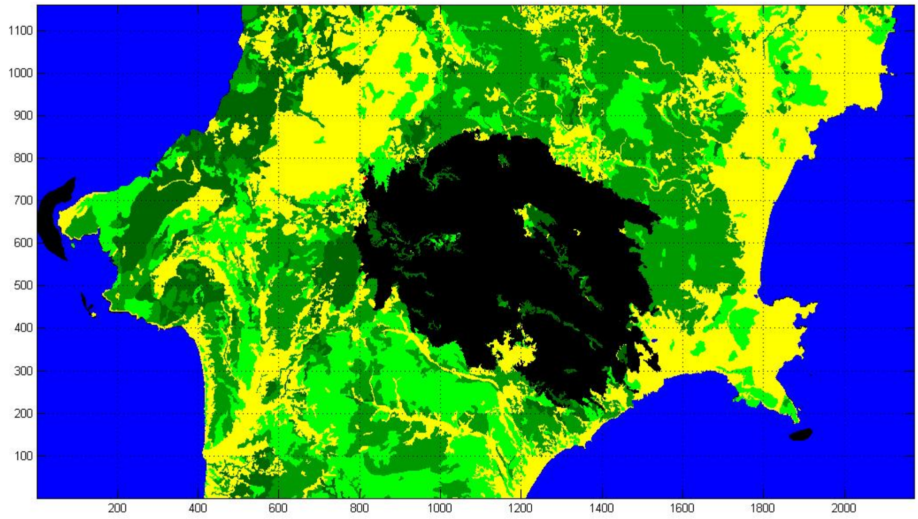

Figure l: Satellite picture of the burned area. The final bumed area is depicted with black color. Density of vegetation is levels of green is also shown. Yellow color presents areas without significant source of fuel.

Simulations were run using the values reported in table 1 (see also Alexandridis et al., 2008) using Matlab as our programming environment.

Table 1: Nominal values of the model parameters.

Parameter	**Value**
p_h	0.58
a	0.08
c_1	0.045
c_2	0.13

The results of simulation are shown in figure 2. A comparison with figure 1 shows that the bumed area predicted by the model is quite close to the real one. As it is shown the proposed model is able to forecast in an efficient way the final burned area taking into account that we did not model the firefighting tactics. It is worthy mentioning that the simulation time was about 3 min on a 2 Quatro Core Intel Xeon with 4 GB RAM running at 3.0 GHz.

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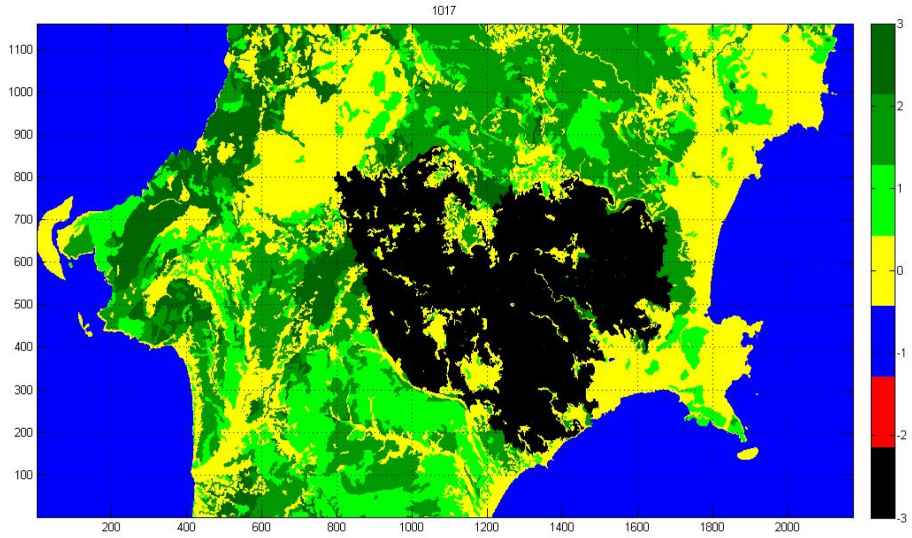

Figure 2: Simulation evolution of the fire-front

4. Conclusions

The need for modelling the evolution of wildand fires and minimizing their negative consequences is constantly increasing and becomes one the most vital challenges in contemporary ecology and risk assessment. Questions about fire spread dynamics in heterogeneous landscapes have been difficult due to the gap between the time and space scales ranging from chemical reactions to velocity and heat transfer patterns and from altitude changes to type and density of vegetation. Over the past years it has been shown that phenomenological computational statistical-mechanics models based on both combustion experimental and theoretical analysis, computational fluid dynamics concepts can be used to forecast in an adequate manner the evolution of wildand fires in large scale heterogeneous environments. Here we used a CA model that we have developed and has been applied to different real-world wildland fires that occurred in Greece to predict the evolution of the fire that broke out in Rhodes Island in July of 2008 destroying a very large area of forest. We implement the model without changing its parameters, i.e. without fine-tuning them to the particular case. Our simulation results reveal that the proposed model is robust in that is able to predict satisfactory the final pattern of the burned area. Differences between our simulation results and the real-final burned area might be attributed mainly to the following reasons. Firstly, we considered a fixed pattern of both wind direction (set to west) and power (around 5 bf). Secondly we did not model firefighting tactics developed on the scene. In a previous study we we have developed a method for simulating fire suppression actions based on air tanker attacks utilising technical specifications as well as operational capabilities of the aircrafts (Alexandirids et al., 2011). Finally, the high heterogeneity of the landscape and heat release may result to complex wind-flow patterns near the surface that in principle can influence dramatically the evolution of the fire front. Hence, the coupling of the proposed CA model with CFD might enhance the model’s efficiency. Yet, dramatic increases of the computational cost should also be taken into account as one has to solve the Navier-Stokes or turbulent models like the k-ε one for every time step of the CA simulation. In this case one has to resort to massive parallelization in order to account for efficient applicability.

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