Simulation of Wildland Fires in Large-Scale Eterogeneous Environements

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This paper presents a computational methodology for predicting the evolution of fire fronts on wild forest landscapes, based on Cellular Automata (CA). The CA framework takes into account various microscopic/detailed and macroscopic factors that affect the spread of fire including the vegetation type, density and height, the wind field, the terrain slope, the spotting fire transfer mechanism as well as suppression tactics. The model was successfully applied to a large scale wildfire that occurred in the mountain of Parnitha, Greece in 2007.

1. Introduction

Uncontrolled forest wildland fires have been the cause of numerous irreversible environmental damages with serious negative ecological and socio-economic consequences including loss of human lives, flora and fauna bio-diversity extinction, rare-species destruction, habitant fragmentation, floods, loss of timber harvest capability, economic loses in the tourism sector, air pollution and climate change (Bergeron and Flannigan, 1995). According to the official publication of the European Commission (EUR 22312 EN) only in 2005 the total burnt area in the high-risk southern European Member States (Portugal, Spain, France, Italy and Greece) was around 590000 ha as the result of a total of 73325 fires, while the total death toll was 41 people most of them fire-fighters. Quantifying in a systematic and efficient way the process of the fire spread is of outmost importance and factors such as weather/climate conditions (wind field, air humidity and temperature), characteristics of fuel (type and structure of the vegetation, moisture and density), landscape/earth features (slope, fragmentation and natural barriers) as well as human interventions are the key elements for succeeding in it (Fons, 1946; Albini and Brown, 1996). However, due to the inherent complex mechanisms, often poorly understood, deploying at different time and space scales, and the interplay between the aforementioned factors, such a task is far from simple, yet a challenging one. In both cases, the strategical or tactical war against the wildfires has much to benefit from a tool that could predict the spread of the fire in

space and time. Moreover such a tool would be also useful in the case of controllable fires which are often used as an important rangeland management tool in Savanna-like areas.

A tool for predicting the wildfire spread would have to take into account external factors like meteorological data as well as the specific characteristics of the terrain. Most important factors that affect the rate of spread and shape of a forest fire front are the fuel type (type of vegetation) and humidity, wind velocity and angle, forest topography (slope and natural barriers), fuel continuity (vegetation thickness), and spotting which is a phenomenon where burning material is spread by the wind or other reasons to areas that are not adjacent to the fire front.

This work presents an enhanced methodology for predicting the spread of a wildfire that is based on the CA framework. Special care has been taken to formulate the rules that define the interactions between the adjacent cells, so that all the major factors that affect the fire spread are taken into account while the methodology also incorporates an attempt to model the spotting phenomenon. The resulting model was applied to simulate the evolution of a wildfire that swept through the National Park of Parnitha in 2007. It should be noted that the specific characteristics of the particular terrain with steep changes in the altitude enable to draw useful conclusions regarding the effect of the slope on the fire spread while case studies of many other fire models that have been proposed in the literature were applied mostly on relatively flat terrains. Also the comparison between the real fire front data and the simulation was used to fine-tune some of the model parameters: a nonlinear optimization problem was wrapped around our simulator in order to determine the values of those parameters that minimize the differences between the real-case and the simulated results.

2. The CA Model

The model uses a two dimensional grid splitting the terrain to a number of cells. Each cell represents a small patch of land and its shape has been chosen to be square, thus offering eight possible directions of fire spreading.

Each cell is characterized by a finite number of states which evolve in discrete time. The possible states are the following:

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. The state of a cell is two, when the cell contains forest fuel that has not ignited. The state of a cell is three, when the cell contains forest fuel that is burning. The state of a cell becomes four, when the contained fuel has been burned down. In summary, 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 when a cell catches fire at the current time step, the fire can be propagated to the neighboring cells at the next time step with a probability p_{burn}. This probability is a function of various parameters and it is calculated using the flowing formula

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

where p_h denotes the constant probability that a 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; p_{den}, p_{veg}, p_w, p_s are the fire propagation probabilities that depend on the density of vegetation, the type of vegetation, the wind speed and the slope respectively. 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., 2008)

## 3. The Case Study and Simulation Results

The proposed methodology was applied for predicting the spread of a real fire incident that took place in the mountain of Parnitha on June 27, 2007. The fire was eventually put under control after three days having destroyed an area of about 6000 ha and caused an inestimable environmental disaster. The fire was so severe that embers, ashes and dense smoke covered the sky and filled the air of Athens. The region of Attica suffered one of the biggest large-scale environmental disasters ever. Fire-fighters battled against blazes with the help of around ten air tankers and two water-dropping helicopters. The fire evolved rapidly under conditions of heterogeneous mountainous landscapes, density and characteristics of the vegetation as well as significant meteorological changes.

Figure 1 illustrates a satellite picture depicting the burned area. The yellow line on the picture marks the area for which our simulation was run.

The simulation results of the fire spread are shown in figure 2. The final burned area is depicted with black color while the red contours show the advancement of the fire front in time-intervals of 3 hours. A comparison with figure 2 shows that the burned area predicted by the model is quite close to the real one. it is clear that the proposed model captures quite satisfactory the behavior of the fire, which is a rather challenging task taking into account the difficult heterogeneous terrain as well as the varying vegetation type and density.

4. Concusions

The proposed CA simulation framework takes into account the major-macrosopic factors that determine the course of the fire like the vegetation density, type, height moisture air content, the wind field and the slope-terrain changes. The methodology has been tested in the simulation of one of the most catastrophic fire incidents in Greece over the last 50 years. The particular event has the potential to serve as a benchmark for such prediction models as the terrain on which it took place as well as the presents significant heterogeneities over the grid for almost all of the parameters affecting the fire spread. The results demonstrate the success of the proposed approach, as well as its usability in testing what-if scenarios and therefore could ultimately be used as an aided tool for the real-time risk management.
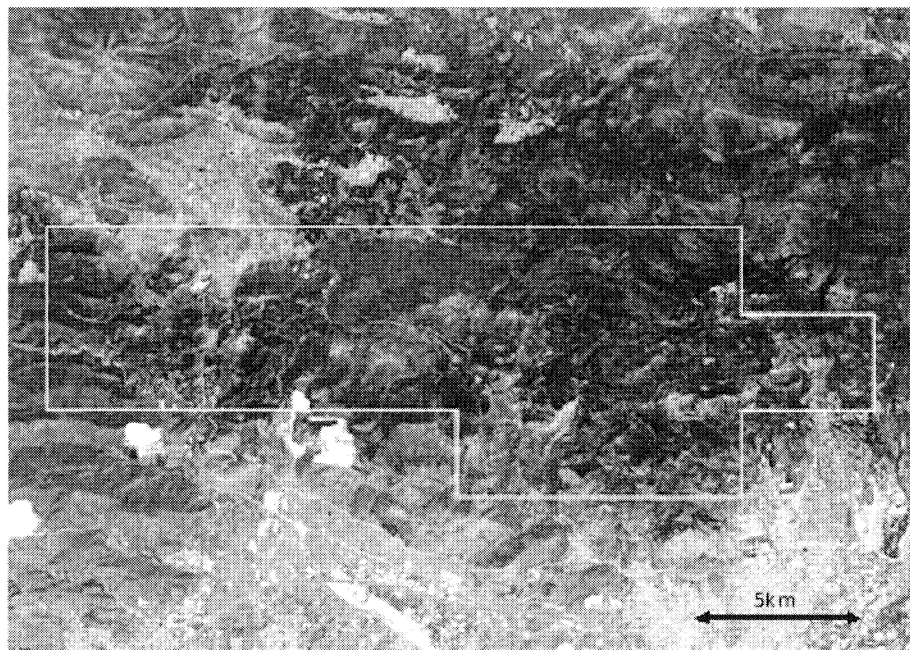
Figure 1: Satellite picture of the burned area.
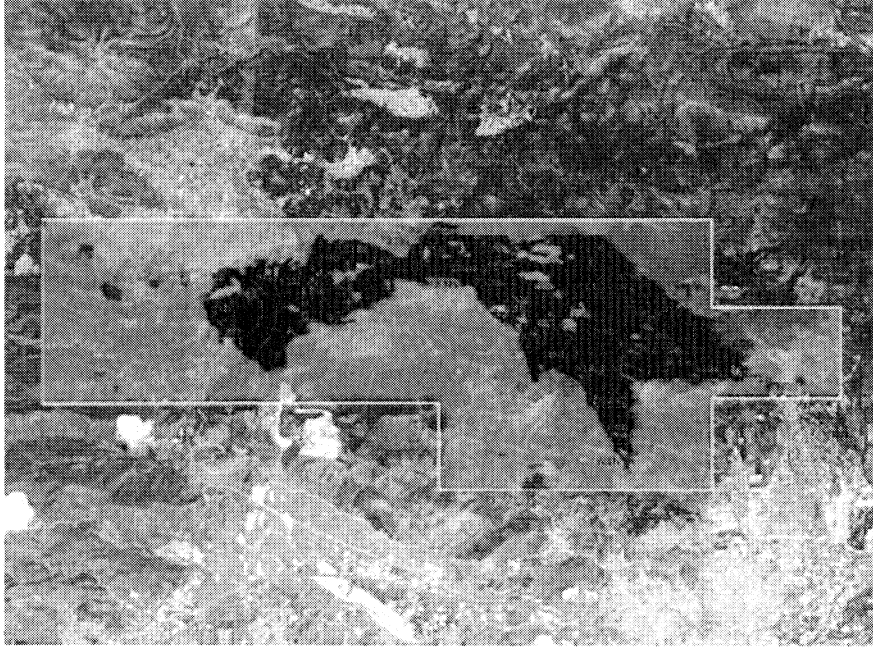
Figure 2: Simulation evolution of the fire-front

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