A Cellular Automata Model for Fire Spreading Prediction

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Abstract: - The modeling of fire spread in a flammable area is an interesting and challenging issue, widely studied in literature. Some of the models used for fire front evolution prediction are based on Cellular Automata (CA) approach, and they have shown a good agreement with other models and with experimental data. In this paper, the authors propose a new approach to this kind of models, introducing an "ignition probability" in the transition rules. This probability depends on several parameters, such as number of burning neighbors, wind direction and speed, land slope, fuel typology, etc.. As a starting approach, the number of neighbors that already burn seems to be the more interesting parameter to be considered in the ignition probability. Thus, the evolution of each single cell is governed by the presence of burning cells in its neighbourhood and, according to reality, the simulated fire spread does not present a regular shape of the fire front.

Key-Words: - Cellular automata, fire spread, environmental impact, modeling.

1 Introduction

The control of fire spreading in an environment is one of the most challenging aspect of environmental research, since fire, of course, heavily affects the quality state of forests and the public safety. Since the impact of fire on environment is critical, in the last years the interest of researchers in models able to simulate the evolution of a fire front is increased significantly. The fire front is defined as the line that separates burned and unburned parts of a forest.

The most important parameters that influence the spreading of fire are the presence of fuel and its typology, the slope of the terrain and wind direction and speed. The rates of fire spread, i.e. the fire front speed at each point in a forest, can be given by some previously calculated "rate of fire spread" distribution [1] or properly evaluated on a theoretical base (for instance, see [2]).

The aim of a model developed for the prediction of fire spreading is mainly the determination of how the fire front evolves in time, in a given environment and with various weather conditions [3]. An efficient prediction of fire spreading can be useful in the security strategy design and in the choice and implementation of defence tools.

The final purpose of a fire spreading model is to aid the real-time decision support system and to help the determination of strategies for fire control and land use planning. In addition, these models can be used for the simulation based training of fire brigades.

The possibility to combine this kind of models with a Geographical Information System (GIS) and satellite imagery has been explored in literature (see for example [4]); the main idea is to give as input the fire front image from satellite at a certain time t_1, the weather conditions and the land data (shape and height), and to obtain in output the fire front position at any time $t_2 > t_1$. This approach will be proposed in this paper, even with some corrections and differences.

Usually fire spreading models are classified in stochastic and deterministic models. The first ones have an empirical intrinsic feature and simulate the more probable evolution of fire front, in average conditions. They are usually tuned on experimental data, both from laboratories and from outdoor real fires.

On the other hand, deterministic models deduce the behavior of fire front directly from physical conservation laws governing the evolution of the system composed by the system and the environment. In particular, these models have two different subcategories: the Vector models and Cellular Automata (CA) models. The first ones evaluate the evolution according to a specified growth law and they take a standard geometrical shape. If burning conditions are uniform, a single shape can be used to determine the fire size, the perimeter over time and the area by means of the use of fractals [6]. More complex Vector models use wave propagation techniques based on Huygen's principle (see, for example, [4] - [9]), and also determine the temperature fields and the fire propagation simultaneously by performing turbulent fluid flow calculations [10].

CA models, instead, apply the main idea of Cellular Automaton proposed by Von Neumann and then detailed by Wolfram, and they represent a suitable tool to model the behavior of fire front because of their intrinsic features. Several types of Cellular Automata models for fire spreading have been introduced in the literature: Probability-driven models [11], fractal models [12], etc..

The reason behind the popularity of CA can be traced to their simplicity and to the enormous potential they hold in modeling complex systems. Cellular automata can be viewed as a simple model of a spatially extended decentralized system made up of a number of individual components (cells). The communication between constituent cells is limited to local interaction. Each individual cell is in a specific state which changes over time depending on the states of its local neighbors. The overall structure can be viewed as a parallel processing device. However, this simple structure, when iterated several times, produces complex patterns displaying the potential to simulate different sophisticated natural phenomena.

A more detailed description of Cellular Automata main ideas and features can be found in the papers by Von Neumann [13] and Wolfram [14], and a summary has been furnished by the authors in [15].

In this paper, the authors present an improvement of the CA models for fire spreading present in literature. The new idea is to introduce a probability of fire ignition, that has to be related to burning neighbors, fuel typology, wind direction and land slope. As a starting approach, the ignition probability will be assumed to be constant in time and uniform in space, but dependent on the number of burning neighbors, since it seems to be the more interesting parameter to be initially considered. Let us underline that the other parameters dependences have to be kept in mind and inserted in a more detailed analysis, to be presented in a forthcoming paper.

2 Background on Cellular Automata

From a theoretical point of view, four main ingredients play an important role in cellular automata models:

- *The physical environment*

This defines the *universe* on which the CA is computed. This underlying structure consists of a *discrete lattice of cells* with a rectangular, hexagonal, or other topology. Typically, these cells are all equal in size; the lattice itself can be finite or infinite in size, and its dimensionality can be 1 (a linear string of cells called an *elementary cellular automaton* or ECA), 2 (a grid), or even higher dimensional. In most cases, a common—but often neglected—assumption, is that the CAs lattice is embedded in a *Euclidean space*.

- *The cells' states*

Each cell can be in a certain state, where typically an integer represents the number of distinct states a cell can be in, e.g., a binary state. Note that a cell's state is not restricted to such an integer domain; a continuous range of values is also possible, in which case we are dealing with *coupled map lattices* (CML). We call the states of all cells collectively a CAs *global configuration*. This convention asserts that states are local and refer to cells, while a configuration is global and refers to the whole lattice.

- *The cells' neighbourhoods*

For each cell, we define a neighbourhood that locally determines the evolution of the cell. The size of neighbourhood is the same for each cell in the lattice. In the simplest case, i.e. a one-dimensional lattice, the neighbourhood consists of the cell itself plus its adjacent cells. In a two-dimensional rectangular lattice, there are several possibilities, e.g., with a radius of 1 there are, besides the cell itself, the four north, east, south, and west adjacent cells (*von Neumann neighbourhood*), or the previous five cells as well as the four north–east, south–east, south–west, and north–west diagonal cells (*Moore neighbourhood*); see Fig. 1 for an example of both types of neighbourhoods. Note that as the dimensionality of the lattice increases, the number of direct neighbours of a cell increases exponentially.

- *A local transition rule*

This rule acts upon a cell and its direct neighbourhood, such that the cell's state changes from one *discrete time step* to another (i.e., the system's iterations). The CA evolves in time and space as the rule is subsequently applied to all the cells *in parallel*. Typically, the same rule is used for all the cells (if the converse is true, then the term *hybrid* CA is used). When there are no stochastic components present in this rule, we call the model a *deterministic* CA, as opposed to a *stochastic* (also called *probabilistic*) CA.

As the local transition rule is applied to all the cells in the CAs lattice, the global configuration of the CA changes. This is also called the CAs *global map*, which transforms one global configuration into another. This corresponds to the notion of *computing a function* in automata theory. Sometimes, the CAs evolution can be reversed by computing past states out of future states. By evolving the CA backwards in time in this manner, the CAs *inverse global map* is computed. If this is possible, the CA is called *reversible*, but if there are states for which no precursive state exists, these states are called *Garden of Eden* (GoE) states and the CA is said to be *irreversible*.

Finally, when the local transition rule is applied to all cells, its global map is computed.

3 CA for fire spreading

In this section, the CA model for fire spreading is presented. The model has been implemented in the Wolfram Mathematica^{tm} framework.

A forest area can be easily simulated as the cellular space of a Cellular Automaton, acquiring the given area by a satellite image and converting it in a two dimensional array of identical square areas of a given side length. This side length can be chosen according to the needed resolution, but, of course, cannot be less than the pixel image dimension. The elements of the array constitute the cells of the CA.

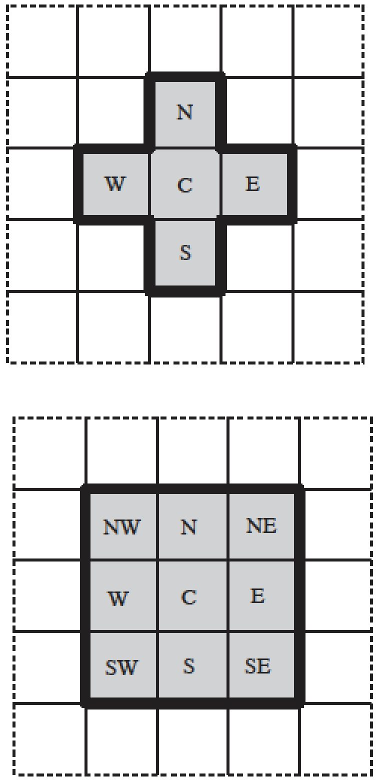

Fig. 1: Two commonly used two-dimensional CA neighborhoods: the von Neumann neighborhood (up) consisting of the central cell itself plus 4 adjacent cells, and the Moore neighborhood (down) where there are 8 adjacent cells.

The state of a cell (i, j) at the time t, can assume 4 values:

(0) represents the "fuel" cell unburned
(1) represents the "not fuel" cell (not flammable)
(2) represents the burning cell
(3) represents the burned cell

Of course, during the acquisition phase, the possible states are only (0) and (1), that respectively refer to not burnable and flammable areas. These states have been represented in a graphical framework, with a binary colour scale, where green cells are the (0) state and gray cells represent (1), as shown in Fig. 2.

In this framework, the fire ignition is simulated by means of a given number of random distributed burning cells, i.e. the initial conditions, that will guide the space evolution of fire spread.

Per each cell (i, j) on the map, the number of burning neighbours N_b is defined with the Moore approach (see Fig. 1).

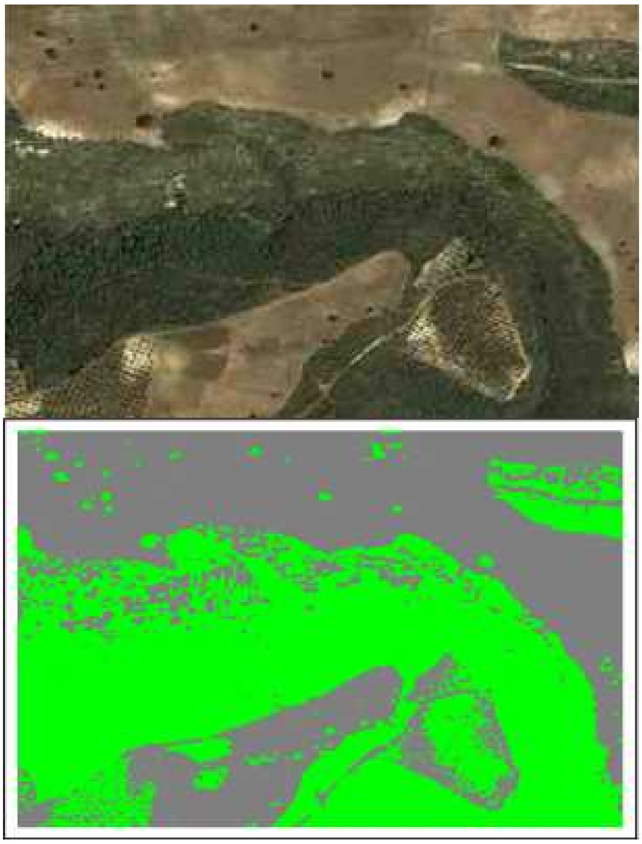

Fig. 2: Input map of the area, given by satellite image (up). In the bottom, converted map, with binary states: green cells stay for burnable states (0), gray cell stay for not flammable state (1).

The transition rules are:

$$\text{If} \quad N_b < 1, \text{ then } \quad (0) \rightarrow (0)$$

$$\text{If} \quad N_b \geq 1 \quad \text{then} \quad \begin{cases} (0) \rightarrow (2) \text{ with probability } p \\ (1) \rightarrow (1) \\ (2) \rightarrow (3) \text{ after a time step} \\ (3) \rightarrow (3) \end{cases}$$

The probability p is related to the number of burning neighbourhood N_b by the following formula:

$$p(N_b) = \frac{N_b}{8} \quad (2)$$

As already said in the introduction, in addition to the dependence from the number of burning neighbours, the probability of ignition should be related also to other parameters, that are fuel typology, wind direction and speed and land slope. In a forthcoming study, the authors will study these dependences, trying also to give an evaluation of the weights of these parameters, by means for example of Analytic Hierarchy Process (AHP) approach, such as the authors suggest in [16].

This transition rules are graphically rendered as a changing in the colour of the cell, for instance, from green (0) (flammable) to red (2) (burning), and then to brown (3) (burned), as it can be noticed in Fig. 3.

In this Figure, in fact, the results of a simulation on a sample map are shown, with 5-15-25 time steps screenshots.

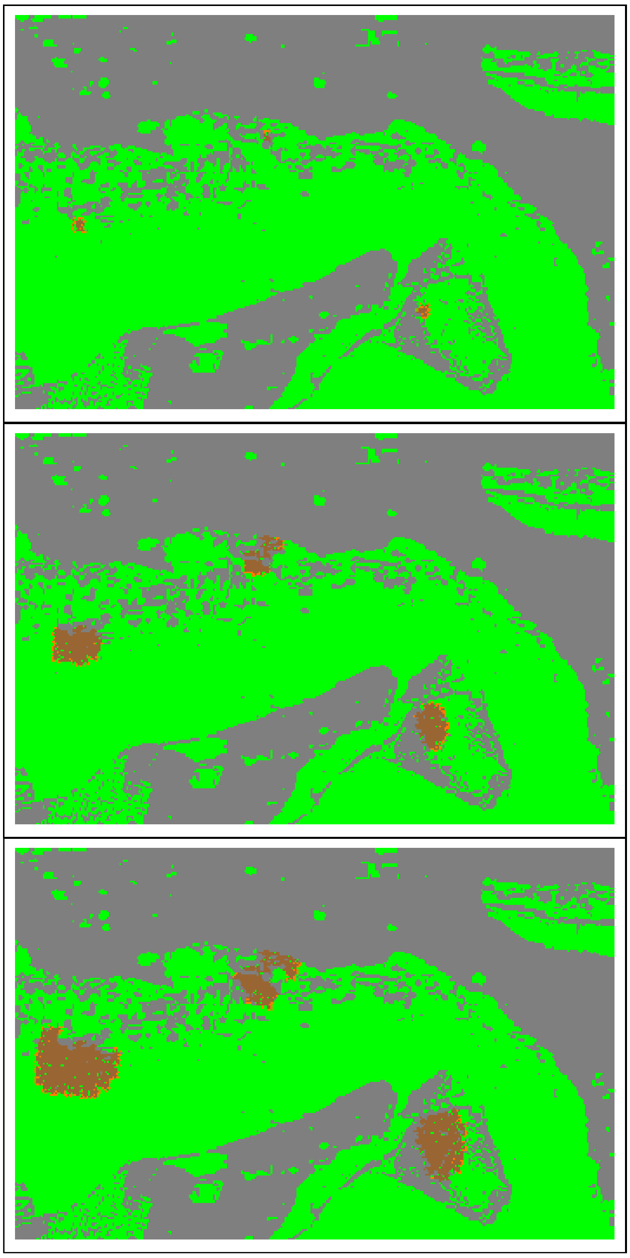

Fig. 3: Fire spreading under the proposed CA model, with three initial burning cells. Three screenshots are shown at 5, 15 and 25 time steps.

Three fires (that are, three burning cells in the CA space) have been chosen as initial conditions. It is easy to notice that the evolution of fire front does not follow a regular shape, due to absence of fuel cells in some region (right-bottom and centre-up fires) and to ignition probability (left fire).

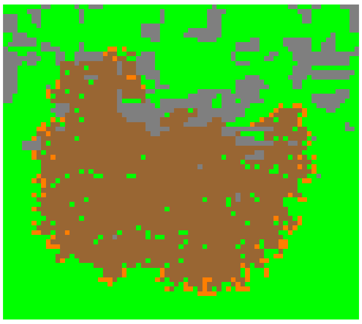

Fig. 4: Final (after 30 time steps) irregular shape of fire on the left of the map.

In particular, left fire final shape (i.e. after 30 time steps, see Fig. 4) shows that some cells stay unburned and a roughly circular fire front is evidenced, as it is experienced in reality (in absence of wind).

4 Conclusions

In this paper the authors presented an application of Cellular Automata models to the simulation of fire spreading in a selected area. This area under analysis can be put as input of the program by means of a satellite image. The conversion to a two dimensional array constitutes the physical space of the CA, which then evolves with given transition rules. These rules are characterized by an ignition probability for the cell, which, in this model, depends only on the number of burning cells in its neighbourhood. At each step of the time loop, if the condition for ignition are fulfilled, the cell burns, otherwise it stays unburned. This random core represents the new approach to a phenomenon that is, in its intrinsic behaviour, stochastic.

The authors postpone to a future work the possibility to introduce in the ignition probability the dependences on other critical factors, such as wind direction and speed, fuel typology and land slope. These parameters have to be properly weighted according to their influence in the burning phenomenon. The evaluation of the weights of each parameter can be performed by means of various decision theories, such as, for instance, Analytic Hierarchy Process (AHP) approach.

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