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A model for predicting forest fire spreading using cellular automata

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Abstract

The model presented, for the first time, in this paper can predict the spreading of fire in both homogeneous and inhomogeneous forests and can easily incorporate weather conditions and land topography. An algorithm has been constructed based on the proposed model and was used for the determination of fire fronts in a number of hypothetical forests, which were found to be in good agreement with the experience on fire spreading in real forests. © 1997 Elsevier Science B.V.

Keywords: Cellular automata; Environmental systems; Forest fire; Modelling; Simulation

1. Introduction

Fires are an integral part of almost all natural area ecosystems, and over the course of many centuries have exerted an exceptionally important influence on the condition and structure of forests in many regions of the planet. The long-term and recurring impact of forest fires ultimately influences the qualitative state of forests, and to a considerable degree governs the distribution of species and associations across diverse areas (Furyayev, 1994). The environmental effects of forest fires are enormous and, therefore, there is a constant demand for more effective fire fighting and management (Good and McRae, 1989).

Modelling and simulation have been applied to fire fighting and management for many years, particularly in order to predict fire behaviour and spread in forests under various scenarios of weather conditions. Generally, the goal of a model for the prediction of fire spreading in forests is the determination of the time-evolving fire front in a physical landscape under various weather conditions. Wind direction and speed are the most important factors in such a model. The fire front is the dividing line between the burned and unburned parts of a forest. The rates of fire

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spread, i.e. the fire front speed at each point in a forest, is given by some previously calculated 'rate of fire spread' distribution (McRae, 1989). A model for fire spreading in forests can be used as a real-time decision support system, in order to enhance the effectiveness of fire fighting strategies (Kessell and Beck, 1991). It can also be used for the determination of strategies for fire control and land use planning, and for the simulation based training of fire brigades (Green and Gill, 1989). Such a model could be part of a system for real time fire front determination. Such a system would combine a geographical information system (GIS) and satellite imagery with a model for forest fire spreading (Beer, 1989). Inputs to such a system would be a satellite image of the fire front at a time t_1, the weather conditions, and the shape and height of the land, i.e. the contour map. The output of this system would be the fire front position at any time $t_2 > t_1$.

The following are four of the most important models for forest fire spreading, developed until now. In the first model the set probability theory is used. Using this model and taking into account initial data on the fire condition, it is possible to calculate an average fire front forecast for any subsequent time (Ivanilova, 1985). The second model has been developed by extending an existing stochastic model, in which the fire spreading process is described as a percolation process. Although the model is general, it has only been applied to city layouts (Hirabayashi and Kasahara, 1988). In the third model, given the initial position of the fire front, the new fire front position is determined using the Huygen's principle (Beer, 1989). In the fourth model the temperature fields and the fire propagation are determined simultaneously by performing turbulent fluid flow calculations (Lopes et al., 1995). In an experimental model, which has also been developed for modelling forest fires (Zhang et al., 1992), the researchers present an experiment on the propagation of a flameless fire on a thin piece of paper which can simulate a real forest fire. The difficulties in modelling and simulation of forest fires are severe, because the problem of predicting forest fire spreading is a highly non-linear problem and the shape of the forest and the different areas in it impose complicated boundary conditions. The models developed until now, are either inaccurate or they demand staggering amounts of computer memory and computation time (Bardley and Clymer, 1993). Furthermore, none of these models can incorporate all the factors affecting the forest fire spreading (Bardley and Clymer, 1993). These factors are: the weather conditions, and especially the wind direction and speed, the complex topography of the landscape and the existence of areas with different rates of fire spread. It is very difficult to describe the action of all these factors using partial differential equations (PDEs). Such an attempt will probably lead to a system of PDEs which will be very difficult to handle. Cellular Automata (CAs), first introduced by von Neumann (1966), are an alternative to PDEs and have been used successfully in modelling physical systems and processes (Toffoli, 1984a. CAs have also been extensively used as models for complex systems (Wolfram, 1994), and have been applied to several physical problems, where local interactions are involved (Chopard and Droz, 1991), (Gerhard and Schuster, 1989), (Gerhard et al., 1990). Because of their discrete nature and their suitability for implementation on digital computers, CAs seem to be appropriate for modelling forest fire spreading.

The aim of this work is to investigate the possibility of using CAs in modelling forest fire spreading. A model based on CAs was developed, in the framework of this research work. This model can easily incorporate all the factors affecting the forest fire spreading. An algorithm was constructed using this model, and it was used for the determination of fire fronts in a number of hypothetical forests. This algorithm is very fast and can run effectively on a personal computer.

2. Cellular automata

CAs are models of physical systems where space and time are discrete and interactions are only local. CAs, first introduced by von Neumann (1966), have been extensively used as models for complex systems (Wolfram, 1994). CAs have also been applied to several physical and technological problems, where local interactions are involved (Karafyllidis and Thanailakis, 1995, 1996), (Weimar et al., 1992). In spite of their structural simplicity, CAs exhibit complex dynamical behaviour and can describe many physical systems and processes. A CA consists of a regular uniform n-dimensional lattice (or array). At each site of the lattice (cell) a physical quantity takes values. This physical quantity is the global state of the CA, and the value of this quantity at each cell is the local state of this cell. Each cell is restricted to local neighbourhood interaction only, and as a result it is incapable of immediate global communication. The neighbourhood of a cell is taken to be the cell itself and some or all of the immediately adjacent cells. The state at each cell is updated simultaneously at discrete time steps, based on the states in its neighbourhood at the preceding time step. The algorithm used to compute the next cell state is referred to as the CA local rule. Usually the same local rule is applied to all cells of the CA.

A CA is characterised by five properties:
1. The number of spatial dimensions (n).
2. The width of each side of the array (w). w_j is the width of the jth side of the array, where $j = 1,2,3,\ldots n$
3. The width of the neighbourhood of the cell (d). d_j is the width of the neighbourhood at the jth side of the array.
4. The cell state.
5. The CA local rule, which may be an arbitrary function F.

The state of a cell at time step $(t+1)$ is computed according to F. F is a function of the state of this cell and of the states of the cells in its neighbourhood at time step t. The case of a two-dimensional CA ($n = 2$), with neighbourhood width $d_1 = 3$ and $d_2 = 3$, is shown in Fig. 1. In this case the neighbourhood of the (i, j) cell consists of the (i, j) cell itself and of all eight cells which are adjacent and diagonal to it. The CA local rule, which calculates the state of the (i, j) cell at time step $t+1$, is a function of the (i, j) cell's own state and of the states of all eight cells in its neighbourhood at time step t.

CAs have enough expressive power to represent phenomena of arbitrary complexity and at the same time they can be simulated exactly by digital computers because of their intrinsic discreteness; i.e. the topology of the simulated object is reproduced in the simulating device (Vichniac, 1984), (Wilding et al., 1991). Mathematical tools for simulating physics, namely Partial Differential Equations (PDEs), contain much more information than is usually needed, because variables may take an infinite number of values in a continuous space. PDEs are used to compute values of physical quantities at points in continuous time. But the values of physical quantities are usually measured over finite volumes at discrete time steps (Toffoli, 1984a). CAs are used to compute values of physical quantities over finite areas (CA cells) at discrete time steps. The CA approach is consistent with the modern notion of unified space-time. In computer science space corresponds to memory and time to processing unit. In CAs memory (CA cell state) and processing unit (CA local rule) are inseparably related to a CA cell (Matzke, 1994), (Omtzigt, 1994). Because of the above reasons, algorithms that are based on CAs run fast on digital computers (Matzke, 1994), (Toffoli, 1984a). More about modelling physics with CAs may be found in (Feynman, 1982), (Minsky, 1982), (Zeigler, 1982).

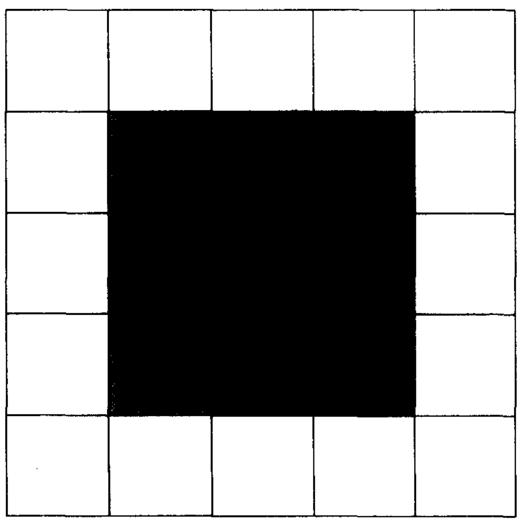

Fig. 1. The neighbourhood of the (i, j) cell comprises the nine grey cells.

Models based on CAs lead to algorithms which are fast when implemented on serial computers, because they exploit the inherent parallelism of the CA structure. These algorithms are also appropriate for implementation on massively parallel computers, such as CAM (Toffoli, 1984b, (Wilding et al., 1991).

3. Description of the basic model

The problem of predicting forest fire spreading can be stated as follows:

> Given a scalar velocity field $R(x, y)$ which is the distribution of the rates of fire spread at every point in a forest, the forest fire front at time t_1, the wind direction and speed, and the height and shape of the land, determine the fire front at any time $t_2 > t_1$.

The forest is divided into a matrix of identical square cells, with side length a, and it is represented by a CA, where each cell of the forest is considered as a CA cell. The number of spatial dimensions of the CA is: $n = 2$. The widths of the two sides of the CA are taken to be equal, i.e. $w_1 = w_2$. The widths of the neighbourhood at sides 1 and 2, d_1 and d_2, of the (i, j) cell are taken to be equal to three. Fig. 1 shows the neighbourhood of the (i, j) cell.

The local state of each CA cell at time t is defined as the ratio of the burned out cell area to the total cell area:

$$S_{i,j}^{t} = \frac{A_b}{A_t} \tag{1}$$

$S_{i,j}^{t}$ being the local state of the (i, j) cell, at time t, and A_b and A_t the burned out and total cell areas, respectively. The state of an unburned cell is zero, whereas the state of a fully burned out cell is 1. $S_{i,j}^{t}$ may take any value in between. At each cell of the CA is allocated a rate of fire spread R, which is the value of $R(x, y)$ at the central point of the cell. The rate of fire spread distribution is assumed to be given by some other model (McRae, 1989). $R_{i,j}$ is the rate of fire spread allocated to the (i, j) cell, and it determines the time needed for this cell to be fully burned out. The state of a cell at time step $t+1$ is affected by the states of all eight cells in its neighbourhood at time step t and by its own state at time step t:

$$S_{i,j}^{t+1} = F(S_{i-1,j-1}^{t}, S_{i-1,j}^{t}, S_{i-1,j+1}^{t}, S_{i,j-1}^{t}, S_{i,j}^{t}, S_{i,j+1}^{t}, S_{i+1,j-1}^{t}, S_{i+1,j}^{t}, S_{i+1,j+1}^{t}) \tag{2}$$

This function is the CA local rule. $S_{i,j}^{t}$ and $S_{i,j}^{t+1}$ are the states of the (i, j) cell at time steps t and $t+1$, respectively. The CA local rule includes the effects, on a particular cell, of the states of all cells in its neighbourhood, as well as the effect of the preceding state of the particular cell itself. If the (i, j) cell is completely unburned and only one of its adjacent neighbours (cells which have a common side with the central cell) is completely burned out, then the (i, j) cell will be completely burned out after a time t_a given by:

$$t_a = \frac{a}{R_{i,j}} \tag{3}$$

a is the cell length (m) and R is the speed of fire spreading (m/s). If only one of its diagonal neighbours is completely burned out, the (i, j) cell will be completely burned out after a time t_d given by:

$$t_d = \frac{\sqrt{2}a}{R_{i,j}} = \sqrt{2}t_a \tag{4}$$

$\sqrt{2}a$ is the length of the diagonal of the cell. If the time step is taken to be equal to t_a, and all cells in the neighbourhood of the (i, j) cell are unburned except for one adjacent cell, then after a time step the (i, j) cell will be fully burned out, i.e. its state will be 1. Suppose that all cells in the neighbourhood of the (i, j) cell are unburned except for one diagonal cell as shown in Fig. 2(a). In this figure burned out areas are grey. After a time step, the (i, j) cell will be partially burned out, as shown in Fig. 2(b). The state of the (i, j) cell will be:

$$S_{i,j}^{t+1} = \frac{a^2 - ((\sqrt{2}-1)^2 a^2)}{a^2} = 2(\sqrt{2}-1) \cong 0.83 \tag{5}$$

In other words, if the state of only one adjacent cell is 1, then the state of the (i, j) cell at the next time step will be 1. If the state of only one diagonal cell is 1, then the state of the (i, j) cell at the next time step will be 0.83. If more than one

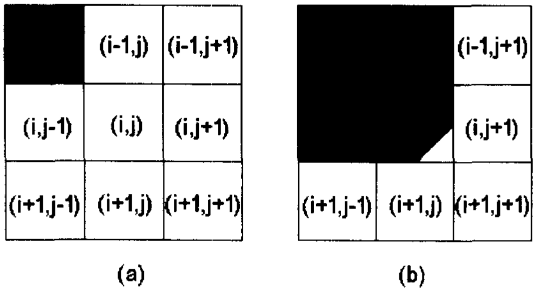

Fig. 2. (a) The cells in the neighbourhood of the (i,j) cell at time step t. Only the $(i-1,j-1)$ cell is fully burned out. (b) The same cells at time step $t+1$. The $(i-1,j-1)$, $(i-1,j)$ and $(i,j-1)$ cells are fully burned out. The (i,j) cell is partially burned out.

cells in the neighbourhood are in state 1, then the state of the (i,j) cell at the next time step will be 1. Consequently, the CA local rule is given by:

$$\begin{aligned} S_{i,j}^{t+1} = {} & S_{i,j}^{t} + (S_{i-1,j}^{t} + S_{i,j-1}^{t} + S_{i,j+1}^{t} + S_{i+1,j}^{t}) \\ & + 0.83(S_{i-1,j-1}^{t} + S_{i-1,j+1}^{t} + S_{i+1,j-1}^{t} \\ & + S_{i+1,j+1}^{t}) \end{aligned} \tag{6}$$

It is possible the value of $S_{i,j}^{t+1}$ to be greater than 1. In this case $S_{i,j}^{t+1}$ is taken to be equal to 1.

A forest is homogeneous, if the value of the rate of fire spread R is the same for all cells. Consider that a fire starts at a point in a hypothetical homogeneous flat forest, and that no wind is blowing. In this case the fire fronts should be circular. This was the first test to the proposed model. Successive fire fronts in a homogeneous flat forest are shown in Fig. 3. The fire fronts are almost perfect circles. Facets are present on the fronts because of the rectangular CA grid. The centre of the circular fronts is the point where the fire was started.

4. Application of the model to hypothetical forests

4.1. Inhomogeneous forests

Almost all physical forests are inhomogeneous, i.e. the value of the rate of fire spread is not the same for all cells. A model for forest fire spreading should be able to determine the time-evolving fire front in inhomogeneous forests. The proposed model has been applied to the flat hypothetical forest of Fig. 4(a). There are two areas with different rates of fire spread in this forest. For the forest of Fig. 4(a), R_1 was taken to be larger than R_2 Consider that a fire starts at the center of this hypothetical forest. The successive fire fronts are shown in Fig. 4(b). It is supposed that no wind is blowing. Fire fronts are of circular shape, and the front advances with equal speed in all directions, in the homogeneous area where the rate of fire spread is equal to R_1. In the area where the rate of fire spread is R_2 ($R_1 > R_2$) the speed of the fire front decreases, and the fronts in and near this area are not circular. The fire fronts are continuous at the boundary between the two areas at all time steps. The time step in the model was taken to be equal to the time needed for the cells with the larger rate of fire spread to be fully burned out:

$$t_a = \frac{a}{R_1} \tag{7}$$

The cells with smaller R need more time steps to get fully burned out.

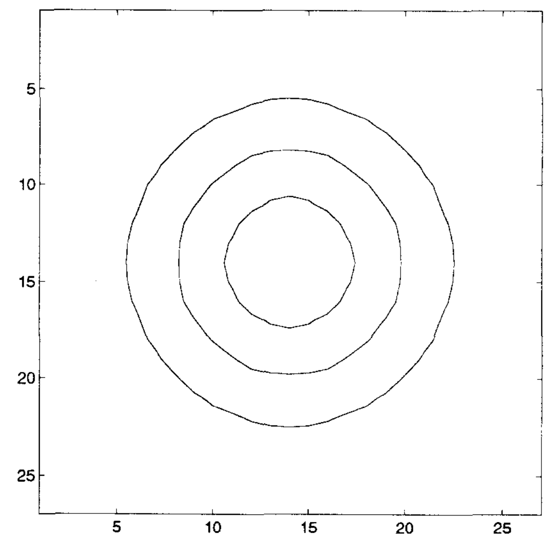

Fig. 3. Fire fronts in a flat homogeneous forest when no wind blows. The fire starts at the centre of the circular fronts. (The units in both axes are arbitrary).

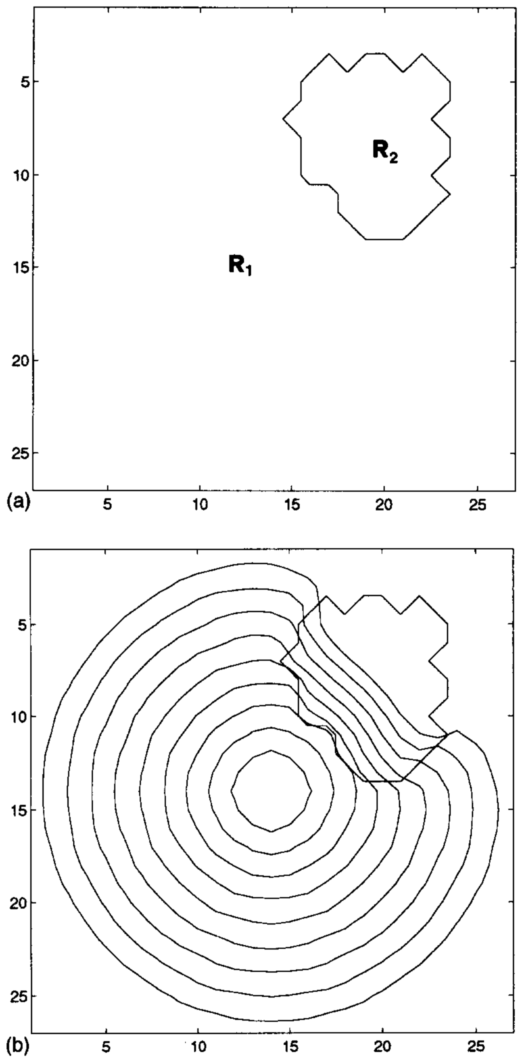

Fig. 4. (a) An inhomogeneous flat forest, $R_1 > R_2$. (b) Successive fire fronts in forest (a). No wind is blowing. (The units in both axes are arbitrary).

It is possible in a forest to exist incombustible areas, such as human constructions, large rocks, rocky hills, etc. The rate of fire spread R in such areas is equal to zero. In Fig. 5(a) the black rectangle represents an incombustible area (e.g. a human construction), in a hypothetical forest. Inside this rectangle $R = 0$ and, consequently the state of the CA cells in this area is always 0. In the rest of the forest. the value of R is everywhere the same. It is supposed that no wind is blowing. Consider that a fire starts at the center of this hypothetical forest. The successive fire fronts are shown in Fig. 5(a). The fire by-passes the small incombustible area, and after a few time steps the fire front becomes almost circular. The black area of Fig. 5(b) represents some physical incombustible area (e.g. a large rock, or a rocky hill). Again a fire starts at the center of this hypothetical forest and no wind is blowing. The fire again by-passes the incombustible area. In this case

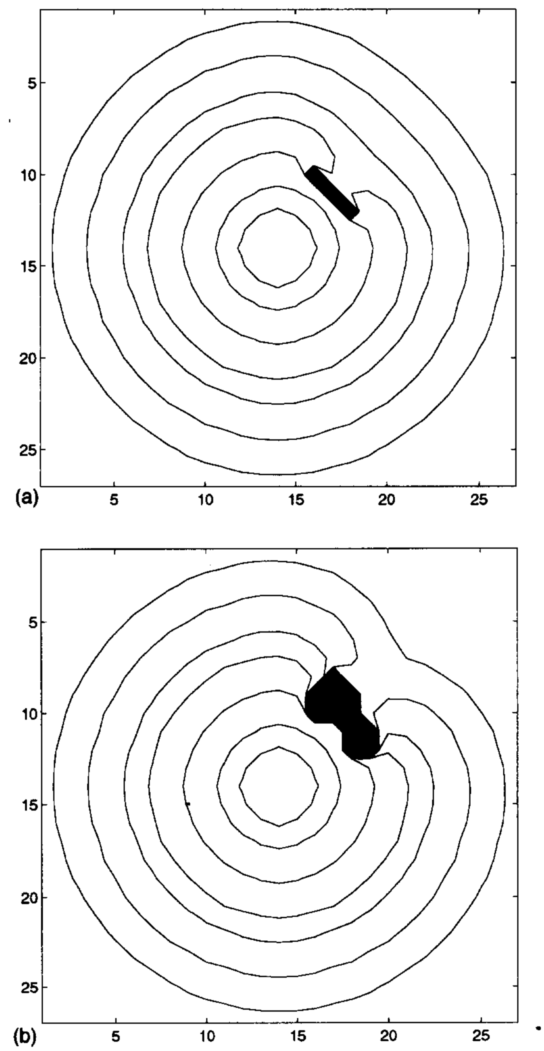

Fig. 5. Successive fire fronts in a flat forest, when no wind is blowing. Black areas in this forest represent incombustible areas. (The units in both axes are arbitrary).

more time steps are needed for the fire front to become almost circular, because the incombustible area is larger than the one of Fig. 5(a).

4.2. Effect of weather conditions on forest fire spreading

The most important weather factors that affect forest fire spreading is the temperature and the wind speed and direction. The effect of temperature is included in the rate of fire spread, i.e. the rate of fire spread in the same forest is larger in summer than in winter, because the fuel in forests is different at different seasons.

The wind speed and direction greatly affect the forest fire spreading and every model for forest fire spreading should incorporate this important factor. Wind speed and direction is incorporated in the proposed model in a very simple manner. Consider that, in the flat homogeneous forest of Fig. 6(a), East is on the right side, West on the left side, North at the top and South at the bottom. The $(i, j+1)$ cell in Fig. 1 is the east cell, the $(i, j-1)$ is the west cell, the $(i-1, j)$ is the north cell and $(i+1, j)$ is the south cell. Cells $(i-1, j-1)$, $(i-1, j+1)$, $(i+1, j-1)$ and $(i+1, j+1)$ are the Northwest, Northeast, Southwest and Southeast cells, respectively. To incorporate the wind into the proposed model, a weight is assigned to each state of the neighbouring cells in the CA local rule given by Eq. (6). After this, the CA local rule takes the form:

$$S_{i,j}^{t+1} = S_{i,j}^{t} + (nS_{i-1,j}^{t} + wS_{i,j-1}^{t} + eS_{i,j+1}^{t} + sS_{i+1,j}^{t}) + 0.83(nwS_{i-1,j-1}^{t} + neS_{i-1,j+1}^{t} + swS_{i+1,j-1}^{t} + seS_{i+1,j+1}^{t}) \quad (8)$$

In the case where no wind is blowing the values of all weights are set equal to 1. If wind is blowing from West towards East, the speed of the fire front will be larger in the direction from West to East and smaller in the direction from East to West. Therefore, in order to model a weak wind blowing from West towards East the weights in Eq. (8) are set to the following values:

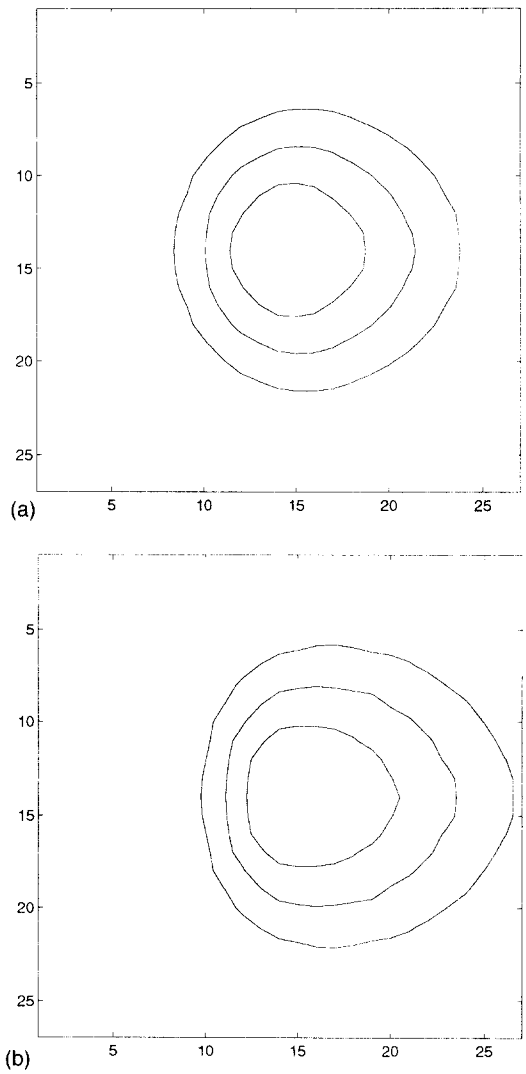

Fig. 6. Successive fire fronts in a flat homogeneous forest when: (a) a weak wind and (b) a stronger wind is blowing from west towards east. (The units in both axes are arbitrary).

$$W = 1.1 \quad e = 0.9 \quad n = 1 \quad s = 1$$

$$sw = 1.04 \quad nw = 1.04 \quad se = 1 \quad ne = 1 \quad (9)$$

Three successive fire fronts produced by the proposed model in this case are shown in Fig. 6(a). Consider again that a fire starts at the centre of a flat homogeneous forest. Changes in wind speed are easily modelled by changing the values of the weights. In the case of a stronger wind, blowing in the same direction as previously, the weights are set to the following values:

$$w = 1.3 \quad e = 0.8 \quad n = 1 \quad s = 1$$

$$sw = 1.1 \quad nw = 1.1 \quad se = 1 \quad ne = 1 \quad (10)$$

Three successive fire fronts produced in this case of the stronger wind are shown in Fig. 6(b). Fig. 6(a) and (b) give the position of successive fire fronts after the same number of time steps.

Changes in both wind speed and direction are easily incorporated in the proposed model. Consider the case where a weak wind blows from West towards East in a flat homogeneous forest. Consider that a fire starts at the centre of the forest. The first two fire fronts (1 and 2) in Fig. 7 are produced by the proposed model when the values of the weights are given by Eq. (9). Immediately after the fire front 2, the direction of the wind changes and the wind is now blowing from South towards North. Additionally, the wind becomes stronger. The values of the weights are set equal to:

$$w = 1 \quad e = 1 \quad n = 0.8 \quad s = 1.3$$

$$sw = 1.1 \quad nw = 1 \quad se = 1.1 \quad ne = 1 \quad (11)$$

and the fire fronts 3 and 4 in Fig. 7 are produced.

4.3. Effect of topography

Almost none of the forests in this planet is flat. The height differences between various points of a forest greatly affect the forest fire spreading. It is well known that fires show a higher rate of spread when they climb up an upward slope, whereas fires show a smaller rate of spread when they descend a downward slope (Lopes et al., 1995).

Height differences are incorporated in the proposed model by using weights as in the case of Section 4.2. The CA local rule takes the form:

$$\begin{aligned} S_{i,j}^{t+1} = S_{i,j}^{t} & + (H_{i-1,j}S_{i-1,j}^{t} + H_{i,j-1}S_{i,j-1}^{t} \\ & + H_{i,j+1}S_{i,j+1}^{t} + H_{i+1,j}S_{i+1,j}^{t}) \\ & + 0.83(H_{i-1,j-1}S_{i-1,j-1}^{t} \\ & + H_{i-1,j+1}S_{i-1,j+1}^{t} + H_{i+1,j-1}^{t}S_{i+1,j-1}^{t} \\ & + H_{i+1,j+1}S_{i+1,j+1}^{t}) \end{aligned} \quad (12)$$

$H_{k,l}$ is a constant that depends on the height difference between the central points of cells (k, l) and (i, j). If $h_{i,j}$ is the height of the center point of the (i, j) cell, and $h_{k,l}$ is the height of the center point of the (k, l) cell, then:

$$H_{k,l} = F(h_{i,j} - h_{k,l}) \quad (13)$$

As a first order approximation, the dependence of $H_{k,l}$ on the height difference was taken to be linear. Fig. 8(a) shows a homogeneous forest in which there exists a hill, or a mountain. The units in all axes are arbitrary. The lines of equal height, i.e. the contour map of this forest, are shown in Fig. 8(b). No wind blows. Consider that a fire starts at the center of this hypothetical forest. The successive fire fronts are shown in Fig. 8(c). In this figure the contour map of Fig. 8(b) is repeated using dashed lines.

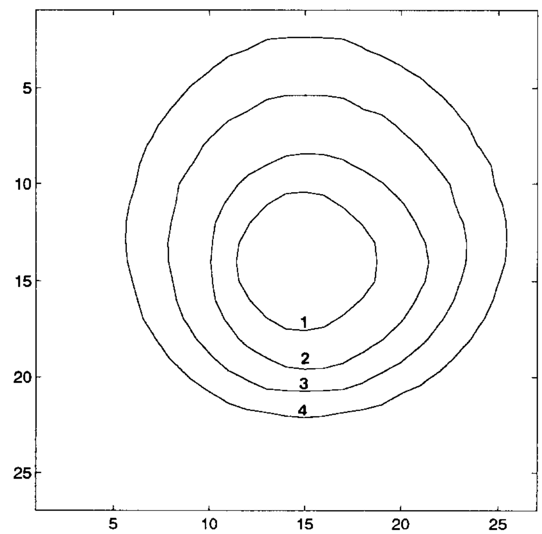

Fig. 7. Successive fire fronts in a flat homogeneous forest when a wind with changing speed and direction is blowing. (The units in both axes are arbitrary).

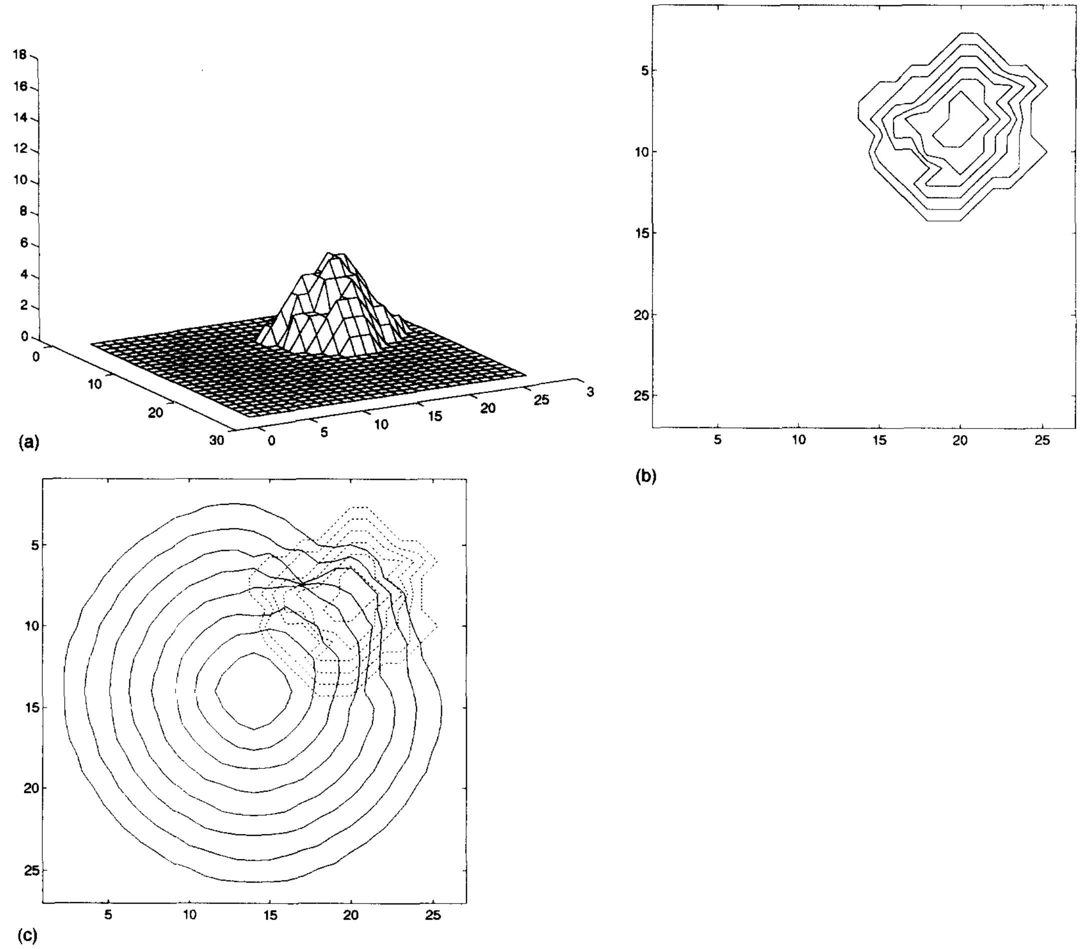

Fig. 8. (a) A homogeneous forest with a hill or a mountain in it. (b) The contour map of this forest. (c) Successive fire fronts in this forest when no wind is blowing. The contour map of the forest is repeated in this figure using dashed lines. (The units in all axes are arbitrary).

The CA local rule which incorporates both the wind and height differences is given by:

$$
\begin{aligned}
S_{i,j}^{t+1} = S_{i,j}^{t} & + (nH_{i-1,j}S_{i-1,j}^{t} + wH_{i,j-1}S_{i,j-1}^{t} \\
& + eH_{i,j+1}S_{i,j+1}^{t} + sH_{i+1,j}S_{i+1,j}^{t}) \\
& + 0.83(nwH_{i-1,j-1}S_{i-1,j-1}^{t} \\
& + neH_{i-1,j+1}S_{i-1,j+1}^{t} \\
& + swH_{i+1,j-1}S_{i+1,j-1}^{t} \\
& + seH_{i+1,j+1}S_{i+1,j+1}^{t}) \qquad (14)
\end{aligned}
$$

4.4. Computation time

An algorithm has been constructed using the proposed model and it was used for the determination of the fire fronts in all aforementioned hypothetical forests. This algorithm was run on a i486/66 MHz machine. The computation time measured on this machine, from the time when the fire starts in a hypothetical forest until the time the forest is fully burned out, was found to be 12 s for a CA with array of 25 × 25 cells, 81 s for a CA with array of 50 × 50 cells and 615 s for a CA with array of 100 × 100 cells. The computation time does not change significantly, when the wind and height difference effects are incorporated, and goes roughly as $O(N^3)$ where N is the number of CA cells in one dimension.

5. Conclusions

A model for the prediction of forest fire spreading has been presented, for the first time, in this paper. The model can determine the fire fronts in both homogeneous and inhomogeneous forests. Weather conditions and land topography can be easily incorporated in this model. In the framework of this research, an algorithm has been constructed based on the proposed model. This algorithm was used for the determination of fire fronts in a number of hypothetical forests. The fire fronts in hypothetical forests, produced by this algorithm, were found to be in good agreement with the experience on fire spreading in real forests. The proposed model can serve as a basis for the development of algorithms that will simulate real fires in real forests. Evidently these algorithms will run fast and could be used not only for planing fire strategies and training, but also as a real-time decision support. Because of the inherent parallelism of CAs, algorithms based on the proposed model can potentially run on a parallel computer.

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