Capítulo 12

Modeling and Simulating Forest Fire Spread

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Abstract: In this work we propose the use of a cellular automata defined on unstructured triangular grids to simulate forest fire propagation. This approach allows us to model computational domains with complex geometries (a domain bounded by a polygonal). It still retains the easy implementation of cellular automata and does not present the anisotropy induced by regular grids. The forest fire spread is modeled by using ignition and burning probabilities for three different fuels. Each cell assumes four states: nonflammable cell, fuel cell, burning cell and burned cell. Ignition probability is modified by effects of type of fuel, ambient temperature/relative humidity slope and wind (intensity/direction). Numerical simulations reproduce the qualitative behavior of forest fires.

keywords: Cellular automata, unstructured triangular grids, ignition burning probabilities, heterogeneous fuels, slope, wind.

12.1 Introduction

Every year forest fires around the world devastate enormous areas of land and cause extensive damage, both to property and human life. Fire can cause soil damage, especially through combustion in the litter layer and organic material in the soil. This organic material helps to protect the soil from erosion. When

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organic material is removed by an essentially intense fire, erosion can occur. Heat from intense fires can also cause soil particles to become hydrophobic. Rainwater then tends to run off the soil rather than to infiltrate through the soil. These fires spread rapidly and without adequate models to forecast their growth, fire-fighters are unable to contain them as efficiently as they would otherwise be able to. In a forest fire management system, computer models of fire are used to understand how fast it would move and to predict what area would it combust before fire occurs. Results can be used for training, planning of fire protections strategies or planes of fire-fighting.

The main fire spread models can be grouped into: empirical (or statistical), semi empirical and physical [Sullivan]. Empirical models predict the most probable fire behavior from average conditions and accumulated information obtained from laboratory, outdoor experimental fire and historical fires.

Semi-empirical models are based on a global energy balance and on the assumption that the energy transferred to the unburned fuel is proportional to the energy released by the combustion of the fuel. A popular semi-empirical models is the Rothermel model which is the basis for many systems in the USA, including BEHAVE, FARSITE, NFDRS, RERAP among others. Cellular automata, first introduced by Von Neumann are an alternative to PDEs and have been used successfully in modeling physical systems and processes.

Because of their discrete nature and their suitability for implementation on digital computers, CAs seem to be appropriate for modeling forest fire spreading and they are considered as semi-empirical models. The work is organized as follows: in section 2 we present a cellular automata model for fire propagation using a unstructured triangular grid; section 3 shows some modeling of the ignition and burning probabilities and how they are affected by slope, temperature, relative humidity and wind, finally we include some conclusions of this work.

12.2 An unstructured triangular Cellular Automata Model for Fire Propagation

Cellular automat's popularity it is due to their simplicity and to the remarkable potential to model complex systems [17]. A cellular automaton is a tuple (d, S, N, f) where d is the dimension of space, S is a finite set of states, N a finite subset of Z^d is the neighborhood and $f : S^N \to S$ is the local rule, or transition function, of the automaton. A configuration of a cellular automaton is a coloring of the space by ,c an element of S^{Z^d} . The global rule $G : S^{Z^d} \to S^{Z^d}$ of a cellular automaton maps a configuration $c \in S^{Z^d}$ to the configuration $G(c)$ obtained by applying f uniformly in each cell: for all position $c \in S^{Z^d}$,$G(c)(z) = f(c(z + v_1), \cdots, c(z + v_k))$ where $N = \{v_1, \cdots, v_k\}$. CA methods have been used for fire propagation simulations using regular grids

([Hernandez], [Karafyllidis], [Quartieri]). [Holland] and [Dunn] suggest the use of irregular geometries to model virtual landscape in order to reduce the bias induced by rectangular grids; [Ortigoza] presented some numerical experiments on unstructured triangular grids showing agreement with their observations. Thus in this work we defined a forest fire spread model on unstructured triangular grids. Besides reducing bias in the movement of information and allowing the representation of real world geometries, its finite element mesh structure provides flexibility to identify neighborhoods, boundary conditions implementations and visualization.

In the present work the area of interest is discretized by using an unstructured triangular mesh, where each triangle is considered as an individual cell and Neumann neighborhoods are assumed.

Let us define our fire spread model by the following assumptions:

1. The spatial domain is discretized by an unstructured triangular grids, each triangle is a cell of the cellular automata.

2. Neumann neighborhoods (a cell and its three neighbors).

3. At each time step, each cell takes one of the following four values:
(0) Representing a nonfuel cell (not flammable).
(1) Representing a fuel cell.
(2) Representing a burning cell.
(3) Representing a burned cell.

4. Two probabilities are assigned to each cell: p_i ignition and p_q burning probabilities. The first one characterizes the ability of a fuel to catch fire and the second its ability to sustain combustion.

5. Fire spreads from a burning cell to a fuel neighboring cell with probability p_i.

6. Transition rules:
(0) $\rightarrow$ (0) not flammable cell will not catch fire.
(1) $\rightarrow$ (2) with probability p_i.
(2) $\rightarrow$ (3) a burning cell evolves to a burned cell with probability p_q.
(3) $\rightarrow$ (3) burned cells remain burned

12.2.1 Modeling Ignition and burning probabilities

To estimate the ignition probability we use the 13 fuel models defined by [Anderson]:

Assuming a maximum rate of spread MROS=4.02m/s we divide each rate of spread from the third column of table 1 by this quantity to obtain the ignition

Fuel type	ROS(ch/hr)	Mean ROS(m/s)
Group grass and grass dominated		
1 Short grass	78	0.4042
2 Grass and understory	35	
3 Tall grass	104	
Chaparral and shrub		
4 Chaparral	75	
5 Brush	18	0.2026
6 Dormant brush	32	
7 Southern rough	20	
Timber Litter		
8 Closed timber	1.6	??
9 Hardwood litter	7.5	0.0317
10 timber	7.9	??
Slash		
11 Light logging slash	6	
12 medium logging slash	13	
13 heavy logging slash	13.5	

Table 12.1: Anderson 13 fuel models rate of spread.

Fuel type	Residence time in seconds
Grass	25.0641
Shrubs	65.3158
Timber	7077.1

Table 12.2: Residence time for three fuels.

probabilities: 0.1005, 0.0503 and 0.0078 for grass, shrubs and timber respectively. Now, let us estimate the burning probability. The upper size limit for fine fuels is set to 6mm for McArthur forest fire danger meter and 10 mm for the forest fire behavior tables for Western Australia, so we assume these values: diameter size of 6 mm for grass and 10 mm for shrubs. For timber we assumed 16 cm diameter which is close to the mean value 10.4 cm obtained in [Murrieta]. According to [Burrows], flame residence time for individual particles (1-16 mm diameter) increases with particle size with the equation $t_r = 0.871d^{1.875}$, here t_r is the flame residence time in seconds and d is the round wood diameter in mm. We use this equation for grass and shrubs. On the other hand for case of timber, Cheney et al developed an equation to predict residence time of silvertop ash logs. Log diameters ranged from 0.6 cm to 25 cm. So for timber we use $t_r = 1.7d^{1.686}$where t_r is the flame residence time in minutes and d is the round wood diameter in cm. Table 2 summarizes the residence time for the three fuels.

In a 2hrs period of time the burning probability can be estimated as: 0.9965, 0.9909 and 0.0171 for grass, shrubs and timber respectively. To estimate this probability at each time step, we take $\Delta t M = 2$ hour period time, where $\Delta t = radius/MROS$; here M is the number of steps and radius is the average radius of the grid. For a radius of 11.99 m and MROS=4.02m/s we have, $\Delta t = 2.98$seg, M=2414. In this case the burning probability at each time step is $\frac{p_q}{M}$ that gives 0.0004128, 0.0004104 and 0.00000707 for grass, shrubs and timber respectively. Note that at each cell we need to keep a record of the time it has been burning. While the cell is still burning p_q accumulates until the cell burns out.

12.2.2 Modeling Slope Probability

Slope significantly influences the forward rate of spread of surface fires by modifying the degree of preheating of the fuel immediately in front of the flames. In a head fire, this is achieved by changing the flames to a very acute angle and with slopes exceeding the flame propagation process involves almost continuous flame contact. On the other hand, a down slope decreases the rate of spread of surface head fire and a low wind speeds has the effect of converting a head fire into a back fire.

The effect of slope (ground elevation) can be modeled [Butler] by equation

$$R_s = R_0 exp(\beta\theta_s), \tag{12.2.1}$$

where R_0 is the rate spread at zero slope, θ_s is the slope angle in degrees between the center of the burning cell and the center of the neighboring fuel cell

$$\theta_s = \frac{180}{\pi} atan\left(\frac{h_2 - h_1}{r}\right).$$

Here $h_2 - h1$ is the height's difference, r the distance between the centers of the cells and β is a constant. From the data experiments of [Butler] et al we adjusted $\beta = 0.0693$. Thus the ignition probability is modified by the slope effect as:

$$p_i * exp(0.0693\theta_s).$$

12.2.3 Modeling Wind Probability

The combustion rate of a fire is positively influenced by the rate of oxygen supply to the fire, thus the effect of wind speed is a very important factor in the fire behavior and rate of spread. Wind causes the angle of the flame to become more acute. With increased wind velocities the flame are forced into the fuel material ahead of the fire producing a more efficient preheating of the fuel and greater rates of spread in surface head fires. Simplified mathematical descriptions of wind effect on the rate of spread of a fire assume a bulk power law effect with. Exponential functions have also been found to provide an adequate representation of the relationship between wind speed and rate of the spread as reported in literature. An observable effect of the high wind speeds upon the flame front is that at some threshold wind speeds local flame extinction has been theorized to occur. Empirical evidence from February 1967 Hobart fires in Tasmania, Australia, indicated that a very high wind speeds (40-45Km/h) the rate of spread in grassfires decreased with increasing wind speed. A possible explanation put forward by [McArthur] was that as the wind increases above a critical threshold, the flame front in light fuels becomes progressively narrower and fragmented, inducing a decrease in the average rate of fire spread.

He noticed this decrease as wind velocity increase above 26-28 miles per hour (12.07m/s) and from the McArthurt's figure as redrafted for [Rothermel] the maximum rate of spread is 8mi/h (3.57m/s). For our numerical simulations let us define a maximum rate of spread for a forest fire. [Noble] presented weather and rate of spread data for three grassfires in Australia winds between 47 and 53 Km/h result in spread rates between 280 and 380 m/min. The 2005 Wangary fire in the Eyre Peninsula of South Australia had grassfire runs of 215 and 245m/min driven by average wind speeds between 46 and 61 Km/h, [Gould].

Author reported	Mean wind speed at the interval	Mean ROS at the interval
McArthurt/Rothermel	12.07m/s	3.57m/s
Noble	13.88m/s	5.5m/s
Gould	14.861m/s	3.83m/s
Mean	13.6m/s	4.02m/s

Table 12.3: Wind speed and fire spreads.

Table 12.3 summarizes the maximum rates of spread reported for different wind speeds, averaging we obtain our MRO=4.02m/s for a wind speed of 13.6m/s. We add these values to the data obtained by [Mendes] et al for rates of spread at different winds speeds and assuming an exponential relation between rate of spread and wind velocity as [Rothermel], we proceed to fit an exponential curve $f(w) = a * exp(b * w)$.

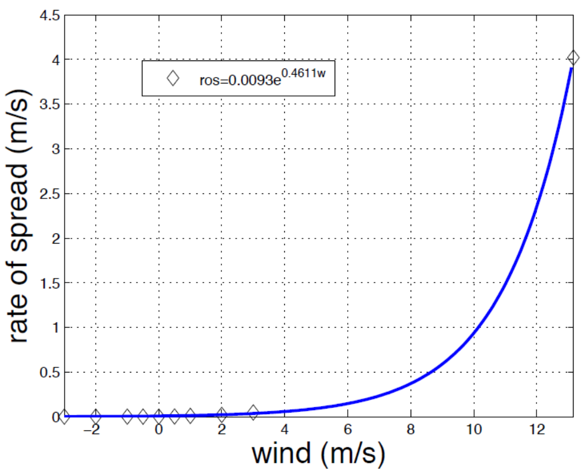

Figura 12.1: Exponential curve to fit the rate of spread as a function of wind speed.

By using a nonlinear least-squares fitting, the coefficients obtained with a 95% of confidence are: $a = 0.009313$ and $b = 0.4611$, the goodness of fit: SSE: 00038, R-square: 1, adjusted R square: 1 and RSME: 0.0065. Figure 12.1 shows the rate of spread at different wind speeds. To model the effect of wind on the ignition probability we take the component of the wind in the direction of the propagation (from the center of the burning cell to the center of a neighboring cell), this increases or decreases the ignition probability. Let $r = (x, y)$ be the components of the direction vector from the center cell to the neighboring cell, let $w = (w_1, w_2)$be the wind vector, the component of the wind in the direction of the neighboring fuel cell is $w_t = \frac{w_1 x + w_2 y}{\sqrt{x^2+y^2}}$. Thus the probability of spread is $p_i * exp(0.4611 w_t)$, here both effects of wind: intensity and direction have been included. Note that the combine effects of slope, wind and fuel type produces

$$p_i * exp(0.4611 w_t) * exp(0.693\theta_s).$$

12.2.4 Ignition probability modified by ambient temperature and relative humidity.

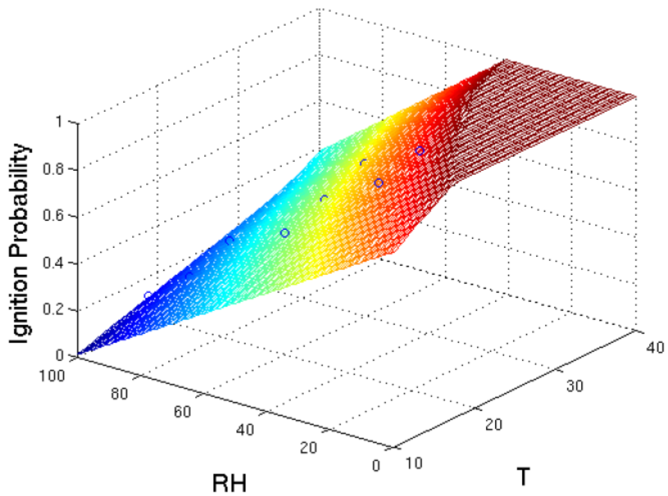

Figura 12.2: Ignition probability as a function of ambient temperature and relative humidity.

Ambient temperature and relative humidity affect the ignition probability of fuel; [Lin] experiments reported that low relative humidity resulted in a higher ignition probability but when higher temperatures occurred, moderate relative humidity also resulted in a higher ignition occurrence.

Figure 12.2 shows a graph of the ignition probability as a function of temperature and relative humidity, the twelve data points obtained by Chau-Chin were quadratic-cubic (quadratic relative humidity/cubic in temperature) extrapolated. Moreover, we assumed that the change in the ignition probability is proportional to the difference between p_i and the given value $p_{(RH,T)}$ of the experimental data, thus the modified ignition probability is given by:

$$p_i + p_i * (p_{(RH,T)} - p_i).$$

We calculate the variations of the ignition probabilities for grass, shrubs and timber due to the variations in relative humidity and ambient temperature, Table 12.4 shows the interval (minimum and maximum) values that these ignition probabilities can take.

Fuel type	p_i	Interval	Interval's length
Grass	0.1	[0.0914, 0.19]	0.0986
Shrubs	0.05	[0.0482 ,0.0975]	0.0493
Timber	0.0078	[0.0079, 0.0155]	0.0076

Table 12.4: Minimum and maximum values that ignition probability can take by the effects of temperature and relative humidity.

12.3 Numerical simulations

12.3.1 Ignition and burning probabilities

Let us consider a 2Kmx2Km square domain, three types of fuels: grass ($0 \leq x < 666$), shrubs ($666 \leq x < 1332$) and timber ($1332 \leq x < 2000$) are considered. Fuel cells are light blue colored.The domain is divided in three vertical strips of equal area with different fuels , the left one with grass, the center with shrubs and the right one with timber. As initial condition we assumed burning cells (yellow color) and their three neighbors which are located at the centers of each third of the domain, Figure 12.3 shows the initial condition.

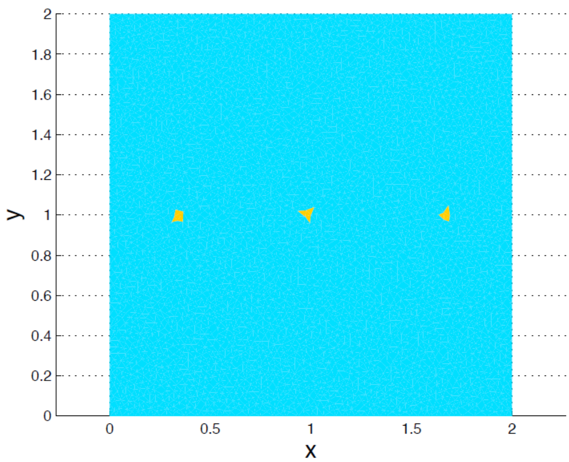

Figura 12.3: Initial condition.

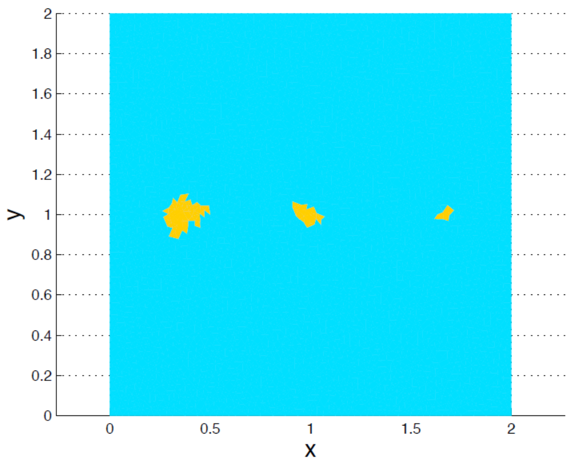

Figura 12.4: Fire spread on grass, shrubs and timber, 500 iterations, $p_q = 0$.

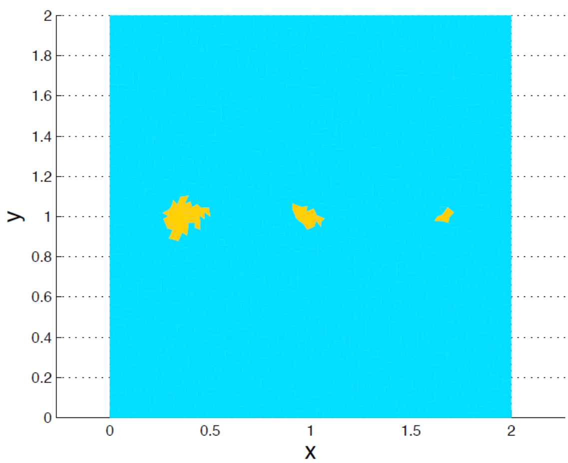

Figura 12.5: Fire spread affected by burning probability, 500 iterations.

At Figure 12.4 we notice that fire spread faster on grass that on shrubs and timber, $p_q = 0$ was assumed so fire spreads and not burn-out occur. On the other hand at Figure 12.5 we observe that the burning probability affects the rate of spread. Stopping the burning prevents the fire spread. Burned cells are red colored. We note that grass and shrubs catch fire easier that tress but they also burn out faster.

12.3.2 Slope effects

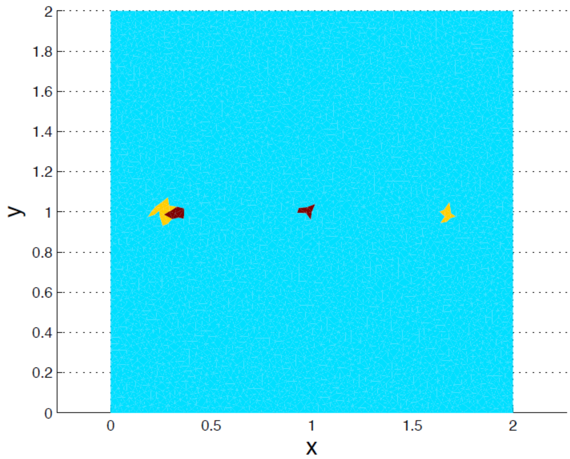

Figura 12.6: Fire spreading uphill and downhill.

Figure 12.6 shows the rate of spread of fire up and down hill. An initial condition of a burning cell (and its neighbors) is located at the center of the square domain. Fire spread at three different slopes: for $1332 \leq x < 2000$. In the central part of the domain (flat) the fire spreads in circular fronts, as soon as it reaches the left and right parts of the domain it changes its rate of spread, rate of spread increases uphill and decreases downhill.

12.3.3 Wind Effects

Direction: Figure 12.7 shows the fire spread under the effect of wind (direction vector field). The initial condition is set as a fire line at the boundary $y = 0$. Fire spread is guided by the direction field.

Intensity: Figures 12.8, 12.9, 12.10 and 12.11 show fire spread under the effect of wind at different intensities. North directed winds of 5, 15, 25 and 35 Km/h. Here three regions of equal area with different fuels are assumed: left grass, center shrubs and right trees. We appreciated the elliptical shape patterns for fire spread under the wind. Backfire is presented at wind of $5Km/h$. Wind effects are higher in grass and shrubs that in trees.

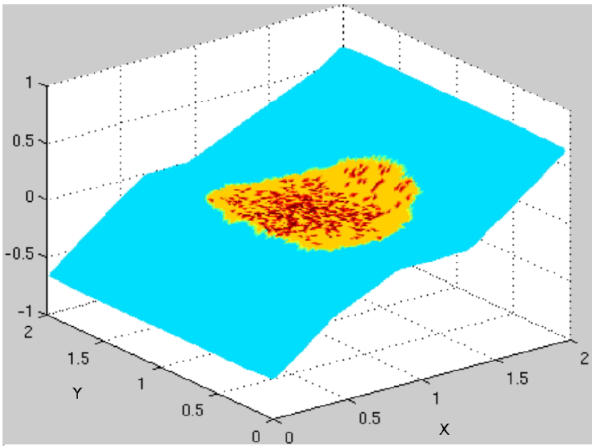

Figura 12.7: A forest fire spread following a wind field.

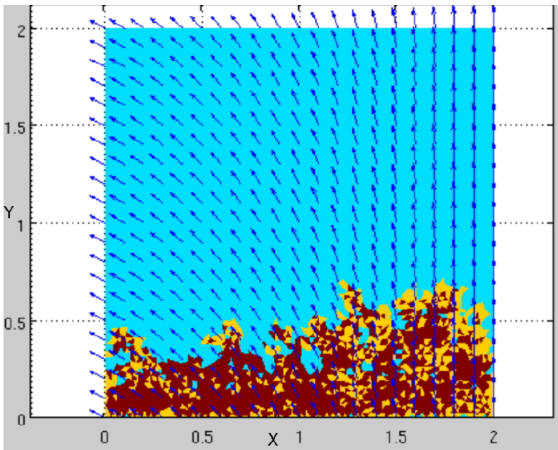

Figura 12.8: Three fuels, 5Km/h wind directed to North, 50 iterations.

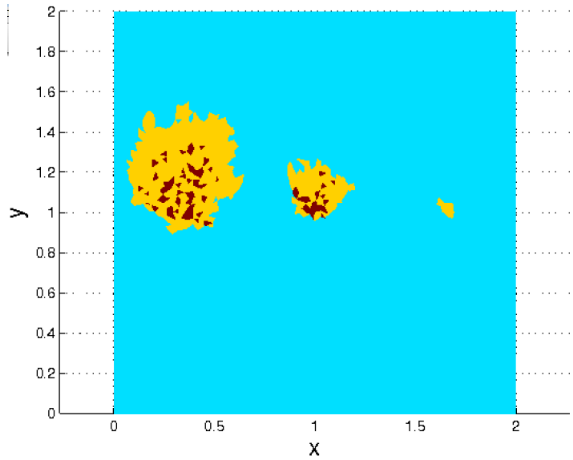

Figura 12.9: Three fuels, 15Km/h wind directed to North, 50 iterations.

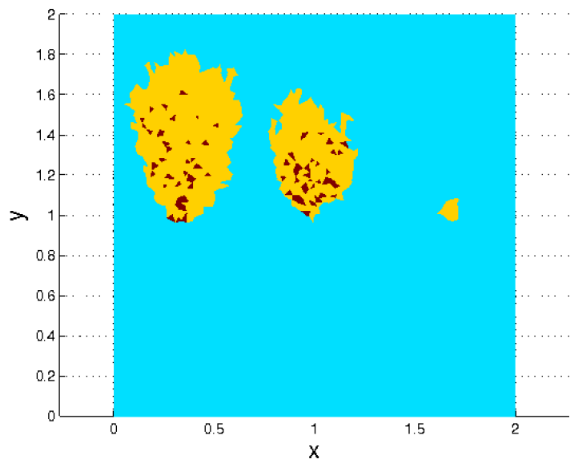

Figura 12.10: Three fuels, 25Km/h wind directed to North, 50 iterations.

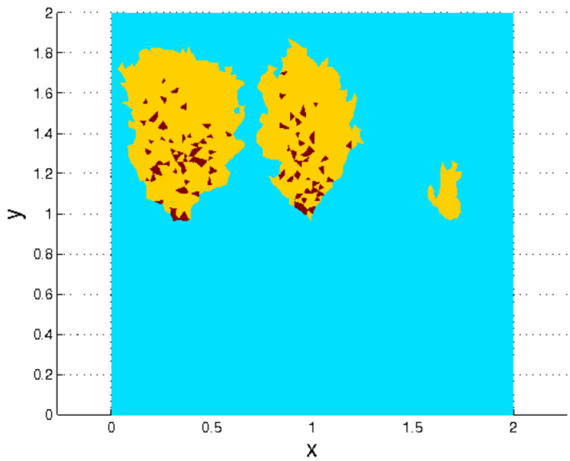

Figura 12.11: Three fuels, 35Km/h wind directed to North, 50 iterations.

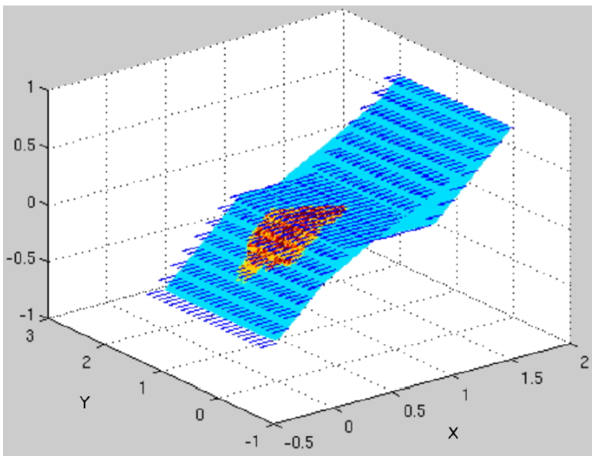

Figura 12.12: Combined effects wind and slope, the wind forced the fire downhill.

Figure 12.12 shows the combined effects of slope and wind, the fire is forced downhill by the effect of wind. As a further work, it is desirable to implement a parallel version of the code in order to reduce the computing time for higher resolution meshes. Fuel moisture should be estimated and its effects on ignition and burning probabilities also be considered; the modification of p_q by the influence of ambient temperature and relative humidity must be modeled. The spotting of fire must be studied and its effects must also be included in the model. Moreover remotely sensed data can be used to estimate density/moisture fuels and to refine the fuels type classification.

12.4 Conclusions

We have proposed the use of an unstructured triangular cellular automata for modeling fire propagation. The fire spread is modeled by a four states cellular automata, here ignition and burning probabilities are defined at each cell. Three types of fuels were considered: grass, shrubs and timber. The effects of slope and wind (intensity/direction) are modeled by exponential functions and they are included in the model by modifying the ignition probability. The effects of ambient temperature are also included in the modification of the ignition probability. The numerical simulations show that the model is appropriate to reproduce the qualitative behavior of forest fire spread and its effects by fuel type, slope and wind.

Acknowledgments
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