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PERCOLATION MODEL FOR WILDLAND FIRE SPREAD DYNAMICS

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The wildland fire is the presence of fire spreading uncontrolledly and burning vegetation areas. Although the fire is a natural disturbance and an essential factor in the maintenance of the diversity and stability of natural ecosystems, some wildland fires can usually generate devastating impacts. The wildland fire impacts are not only threatening the biological diversity, but have also cause large-scale human suffering and economical losses due mainly to pollution of the air and the belongings destroyed by the fire.

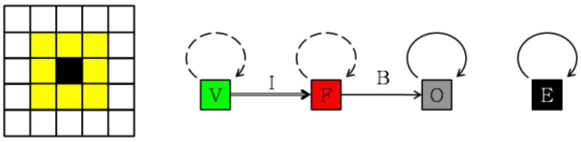
The fire spreads across the landscape consuming the vegetation and this process can be decomposed into four combustion phases, the so called: pre-heating, ignition, combustion and extinction [1]. The fire front is the region of intense flaming combustion where a large quantity of heat released. Part of this heat released is transmitted to the vegetation that yet is not burning, heating it until reaches the ignition temperature. When the vegetation reaches the ignition temperature, the flames rise and the fire front occupies a new position ahead. The flames remain as the vegetation is burnt out.

In this work is proposed a simple model for wildland fire dynamics under flat terrain and no-wind conditions. The model formulation is based on stochastic cellular automata and its dynamics is analyzed qualitatively and quantitatively. Cellular automata are models which assume space, state and time discrete [2].

The model is based on the spatially explicit representation and the landscape is depicted as a square and two-dimensional lattice L of dimensions $L_x \times L_y$. Each cell is defined by: (1) its discrete position (i,j) in the lattice, where $i = 1, \dots, L$ is the column and $j = 1, \dots, L$ is the row; (2) the finite set of internal states variables that describes the possible behavior of the cells in a given time step t which are $S_{(i,j)}^t \in [E, V, F, O]$ where: E is an empty cell, which denotes unburnable cells or without vegetation; V is a vegetation cell, with denote cells with potential to burn; F is burning cell, which denotes a cell whose the vegetation in its inside is burning; and O is burnt cell, which denote vegetation cell that is burned by the fire; (3) the set of finite neighborhood cells $N(i,j)$, where the Moore neighborhood, as illustrated in the Figure 1(a), represents the neighborhood relations in the model and comprises the eight cells surrounding (i^*, j^*) of a central cell (i,j) according with the definition $N(i,j) = \{(i^*, j^*) : |i - i^*| \leq 1, |j - j^*| \leq 1\}$; (4) the transition function that calculate the future cell state as a function of the present cell state and present neighborhood cell states $f: S_{(i,j)}^t \times S_{N(i,j)}^t \to S_{i,j}^{t+1}$, where the time t is also represented by discrete values or time steps. Thus, the time evolution of the model is driven by the interaction between the cell states and the cell neighborhood states. Starting from a given configuration of cells initial states, the cellular automaton self-replicates the sequent cell states. The cellular automata model is stochastic because the state transition function is performed according to probabilities values.

The fire spread is governed by the heat transfer from burning regions to non-burning regions. Thus the fire spread is modeled as a set of ignitions of non-burning regions as the burning regions persist. Stochasticity is used to include the heterogeneity of spatial conditions present in real vegetation patterns and to include random component in the dynamics of combustion and ignition process [4,5,6]. Thus, the dynamics of fire spread is modeled as a stochastic event with an effective fire spread probability S which is as a function three probabilities, which are: (1) the probability D, that determine the proportion of cells with vegetation across the lattice in the model initialization. Thus, for each cell, there is a probability D to its state is vegetation cell and the probability 1-D to it is empty cell; (2) the probability B, that models the combustion, where, in each time step, a burning cell has a probability B to change its state to burnt cell; (3) the probability I, that models the ignition, where, there is a probability I for the fire spreads from a burning cell to a neighbor vegetation cell.

The transition functions between the states are performed according to these probabilities values. The cell state transition diagram is showed in the Figure 1(b). An empty cell is unchangeable and always remains in this state. The fire spread is considered a diffusion contagious process and the fire can spreads only from a burning cell to a neighbor vegetation cell. Thus, the transition V→ F is conditioned for a vegetation cell that has at least one burning cell neighbor. Given two neighbors cells, one burning cell and the other a vegetation cell, in each time step, there is a probability I for the burning cell ignites the neighbor vegetation cell. Once ignited, in each time step, there is a probability B for the burning cell remain burning, otherwise its state changes to burnt cell, which is the transition F→ O.



(a) Moore neighborhood **(b)** Cell state transition diagram

Figure 1 – (a) The Moore neighborhood comprises eight cells (yellow cells) which surround the central cell (black cells). (b) In the cell state transition diagram, arrows indicate the state transitions paths. The double arrow indicates that the transition depends on the neighbor cell state. The round dashed arrows indicate that the state transitions are conditioned by the values of other probabilities.

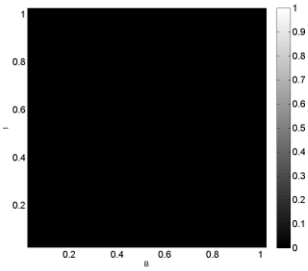
The fire spreads along the lattice following a pathway of interconnected cells which varies as a function of the effective probability S. Studies in percolation theory corroborate that there is a critical value S^*, called percolation threshold, so that when $S > S^*$ always there is this pathway for the fire spreads from a starting cell to some other point inside the lattice [3]. The main question here is how to characterize the probability S in the model.

The existence of the percolation threshold and the consequent description of the critical line as a function of the probabilities D, B and I are investigated using MCS. A set of N MCS are performed using identical lattices and different values of D, B and I. The fire starts at the left border of the lattices and during the N simulations is computed the number of times that the fire reaches the right border of the lattice. If the fire propagates from one side to the other then the fire percolate the lattice. Thus, the approximation of S, denoted by $\langle S \rangle$, is calculated as:

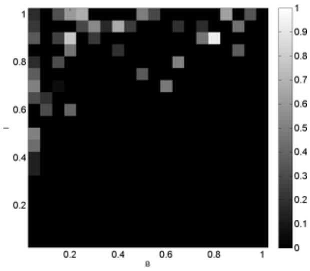
$$\langle S \rangle = \frac{1}{N} \sum_{j=1}^{N} C_j, \qquad (1)$$

where $C_j = 1$ if the fire percolate the lattice and $C_j = 0$ otherwise. The Figure 2 characterizes the values of $\langle S \rangle$ for different values of D varying the values of B and I. For each set of parameters values a set of $N = 1000$ MCS are carried out using one lattice of size 52×52. The color map displays values varying from $\langle S \rangle = 0$ (black) to $\langle S \rangle = 1$ (white). If $\langle S \rangle = 0$ the fire not percolates the lattice, in other words, the fore extinction regime predominates. Otherwise, if $\langle S \rangle = 1$, the fire propagation regime predominates and the fire spreads incessantly across the lattice. The Figs. 4(a)-(f) indicate the existence of a critical line that define a partition on the model parameter space and separates the set of parameters for which a fire can propagate from those for which it cannot. The curve position changes as a function of D. The Figs. 4(a)-4(f) characterizes this critical line in different values of D.

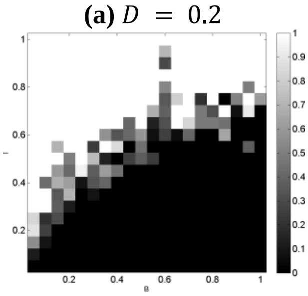
Although the model formulation include only fire spread dynamics under flat terrain and no-wind conditions, the qualitative and quantitative analysis performed in this paper indicate that this model constitutes a qualitative framework for wildland fire spread dynamics simulation. However, for further ecological applications of this model, the relation of the model parameters with meteorological, vegetation and topographical factors remain to be quantitatively established.



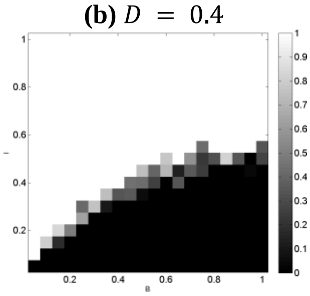
(a) $D = 0.2$



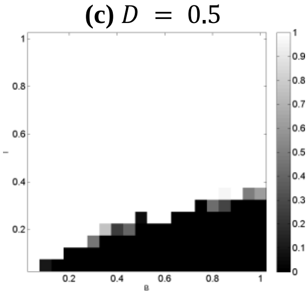
(b) $D = 0.4$



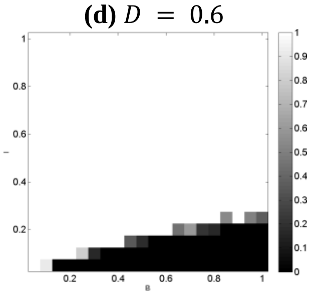
(c) $D = 0.5$



(d) $D = 0.6$



(e) $D = 0.8$



(f) $D = 1.0$

Figure 2 – Values of $\langle S \rangle$ for different values of D varying the values of B and I. A total of $N = 1000$ Monte-Carlo simulations are carried out for each set of values D, B and I using a lattice of size 52×52.

REFERENCES

[1] Pyne, S. J., P. L. Andrews, and R. D. Laven. 1996. Introduction to wildland fire. John Wiley and Sons, New York, New York, USA.

[2] Schiff, J. L., Cellular Automata: A Discrete View of the World (Wiley Series in Discrete Mathematics & Optimization), 2007.

[3] Stauffer, D. and Aharony, A. Introduction to Percolation Theory, 2nd ed. London: Taylor & Francis, 1992.

[4] Hargrove, W. W., Gardner, R. H., Turner, M. G., Romme, W. H., Despain, D. G. "Simulating fire patterns in heterogeneous landscapes". Ecological Modelling, 135: 243 -263 (2000).

[5] Nahmias, J., Téphany, H., Duarte, J., Letaconnoux, S. Fire spreading experiments on heterogeneous fuel beds. Applications of percolation theory. Canadian Journal Forest Research, 30: 1318–1328 (2000).

[6] Favier, C. Percolation model of fire dynamic. Physics Letters A, 330: 396–401 (2004).