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CELLULAR AUTOMATA MODELS. A USEFUL MODELLING TOOL TO DEFINE ENVIRONMENTAL POLICY: THE CASE OF THE FOREST FIRES

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CELLULAR AUTOMATA MODELS AND SIMULATION

An increasing variety of environmental problems are turning to computer simulation. Cellular automata (CA) models are one approach providing a potential method to the study of natural phenomena.

CA models consist of a grid of cells, each cell in one of a number of finite states. Each cell's state is updated in discrete time steps according to a set of rules. These rules depend on the state of the cell or its nearest neighbours in previous or present time steps (Malamud, Turcotte. 2000).

A variety of natural phenomena like avalanches, earthquakes, landslides, biodiversity losses, forest fires or epidemics have been modelled using CA. These systems and models are characterised by an almost uniform and steady input and a dissipating output that satisfies a power-law (fractal) distribution (Bak *et al*. 1990).

The forest fire CA model

In this study a forest-fire CA model has been programmed simulating different fire frequencies, spatial and temporal patterns. The programmed model consists of a square grid, in which at each time step a tree is randomly dropped on a chosen site. Every $1/f_s$ time steps a match is randomly dropped (f_s is the sparking frequency). If a tree falls on an unoccupied cell it is planted. If a match drops on a tree, that tree and all non-diagonally adjacent ones are burned in a fire (Figure 1).

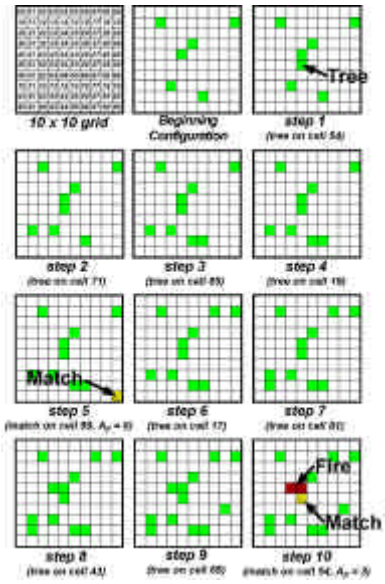

Figure 1. Illustration of how the model works for a grid G=10x10 and a sparking frequency f_s=1/5. Ten time steps are shown. A_F represents the area of each fire (from Malamud, Turcotte. 2000).

These simple rules lead the system to a statistical steady-state behaviour, where the frequency-area distribution of the smaller and medium fires satisfy a power-law (fractal) distribution (Turcotte. 1999b). This behaviour is believed to be self-organised criticality (SOC), a concept introduced by Bak, Tang and Wiesenfeld (Bak *et al*. 1988).

A grid size G, a sparking frequency f_s and a number of steps N_S steps can be defined in the programmed model. The non-cumulative frequency-area distribution of the small and medium simulated fires follow a power-law function:

$$\frac{N_F}{N_S} \approx k * A_F^{-a} \qquad \text{(eq. 1)}$$

where a is a constant, N_F/N_S is the number of fires per time step with area A_F and k is a constant.

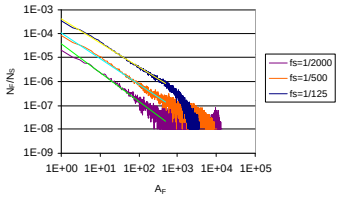

Figure 2. For G=128*128 and N_S=10^6, the graph of N_F/N_S as a function of A_F on a log-log scale suggests a clear correlation with a power-law function, specially for small and medium fires, with a power law exponent α=1.0-1.2.

The model has been run for different grid sizes and sparking frequencies, with resulting α ranging from 1.0 to 1.2. Real forest fire data sets also follow a power-law distribution, but with α=1.3 to 1.5 (Malamud, Turcotte. 2000).

Are big or small fires the main responsible for the overall burned area? The area burned per time step due to fires of size A_F is:

$$\frac{N_F}{N_S} * A_F \qquad \text{(eq. 2)}$$

The percentage of the total burned area caused by fires of size $A_F \leq A_i$ is:

$$cumulated_\%_burned(Ai) = \frac{\sum_{Af=1}^{Ai}(\frac{N_F}{N_S} * A_F)}{\sum_{Af=1}^{Amax}(\frac{N_F}{N_S} * A_F)} \qquad \text{(eq. 3)}$$

This variable plotted against A_F results in the following graph (Fig. 3):

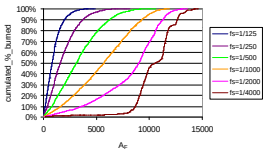

Figure 3. For a G=128*128, N_S=10^6, the graph shows the *cumulated_%_burned* as a function of f_s and A_F.

It can be seen in Figure 3 how for high sparking frequencies small fires are the main contributors to the total burned area, but as the sparking frequency decreases, the percentage contribution of big fires becomes progressively more important. Some forest management guidelines can be clearly drawn from these results.

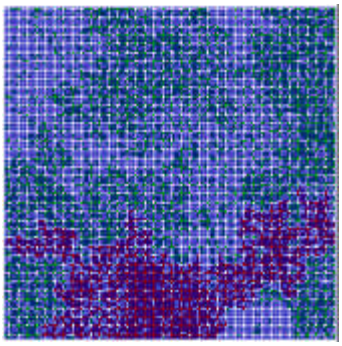

Figure 4. For G=128*128 and f_s=1/250, a typical fire generated by the forest-fire model (in this case A_F=2418).

In relation to temporal pattern of fires, we have studied the *time_elapsed* (number of matches) between a fire and the next one of equal or greater area. As expected, when the model is already in statistical steady state, the elapsed time increases with the size of the fires, and it does so in an exponential way, following:

$$time_elapsed = k * e^{AF*b} \qquad \text{(eq. 4)}$$

where k and b are constants depending on G and f_s.

The tree density r, expressed as number of trees per cell, can be considered as an indicator of the biomass in the forest and therefore it is very relevant to study how is influenced by other parameters, especially by f_s. To do so it has been calculated the average tree density parameter (*mean_r*) for different sparking frequencies:

$$mean_\tilde{n} = \frac{\sum_{i=1}^{Ns}\tilde{n}_i}{N_S} \qquad \text{(eq. 5)}$$

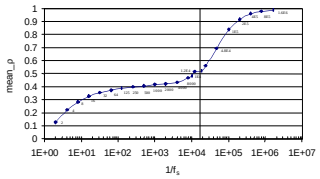

Figure 5. For G=128*128 and N_S=5*10^6, mean_ρ has been calculated for sparking frequencies ranging (1/2:1/10^6). A vertical line has been drawn for $1/f_s$=G (G=128*128=1.64*10^4).

In general, it can be said that *mean_r* increases as the sparking frequency decreases. However, the actual relation is far from expected, presenting an inflexion point around $1/f_s=G$.

It is particularly relevant to keep on studying this parameter because, as maximisation of biomass is often considered a goal in forest management, important policy guidelines may be outlined from the model. Anthropogenic influences in the forest might be understood in the model, at least partially, as altering the sparking frequency.

HAS THIS MODEL ANYTHING TO DO WITH REALITY?

Using data from real forest fires, a power-law relation is also found for their non-cumulative frequency-size distribution.

Both the CA model and real forest fires have robust power-law behaviour.

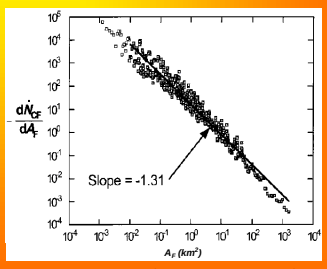

Figure 6. Non-cumulative frequency-area distributions for 4284 forest fires in the United States (1986-1995). From Malamud et al. 1998.

CONCLUSIONS

The forest-fire cellular automata model is very simple, and takes into account no information about forest characteristics or climatic conditions, which clearly determine the evolution of real forest fires. Thus, it cannot be considered an appropriate tool to simulate individual forest fires.

However, despite its simplicity, and considering the many complexities of the initiation and propagation of real forest fires, it is remarkable that the frequency-area statistics looks so similar to real forest fires. Further research should be carried out to check whether those patterns found for the temporal and spatial parameters are also found using real data.

This study constitutes an example of how CA models can address the analysis of some aspects of the general behaviour of complex systems. With a set of very simple rules they can provide similar (macro-level) results compared to those obtained in reality.

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