
A theoretical approach for the spatial distribution of fire breaks in heterogeneous forest landscapes for the control of wildland fires

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Motivation

- Efficient wildland fire-prevention is one of the most challenging and important problems in ecology because of the irreversible environmental and socio-economic damages.
 - Fuel management treatments have been extensively applied at the local scale, but they have a limited influence on the evolution of wildfires at the landscape scale.
 - Observations on real wildland fire cases have evidenced that fire size and severity can be mitigated by proper design of treatments such as fuel segmentation and prescribed burning.
- The problem is how to spatially distribute the fuel management activities across the landscape.*
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What is the main problem here....

Problem too complex, especially for heterogeneous landscapes such as the ones in Greece and Mediterranean countries, so

Need for systematic methodologies (including good mathematical models) to design efficient fire breaks that can inhibit the spread of a wildfire

Aim

Develop a computational tool for the design of fire breaks of forest fires in heterogeneous environments

Factors such as:

- weather/climate conditions (wind field, air humidity and temperature),
- characteristics of the distributed local fuel (type and structure of the vegetation, moisture and density),
- landscape/earth characteristics (slope, fragmentation and natural barriers)
- fire-suppression tactics

are key elements toward this effort (Bergeron and Flannigan, 1995).

Mathematical Models

- Various mathematical models have been proposed to deal with the problem aspiring to shed light on the problem.
 - Depending on the tools, scale and details of description, the modeling efforts can be categorized into three main approaches (Sullivan, 2009a-c).
 - (a) the empirical and semi-empirical ones, mainly based on the statistical analysis of available real-data incidents,
 - (b) the macroscopic/ deterministic, where the fire spread is modeled in the continuum, mainly by using computational fluid dynamics techniques coupled with heat transfer and combustion models, and,
 - (c) the microscopic/grid-based ones, where the phenomenon is usually described in terms of discrete space and time using detailed localized evolution rules governing the propagation of the fire-front to the neighboring areas.
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Mathematical Models: yes but we are not done

Mathematical models are the one of the cornerstones

the Concept of COMPLEXITY IS THE OTHER ONE!

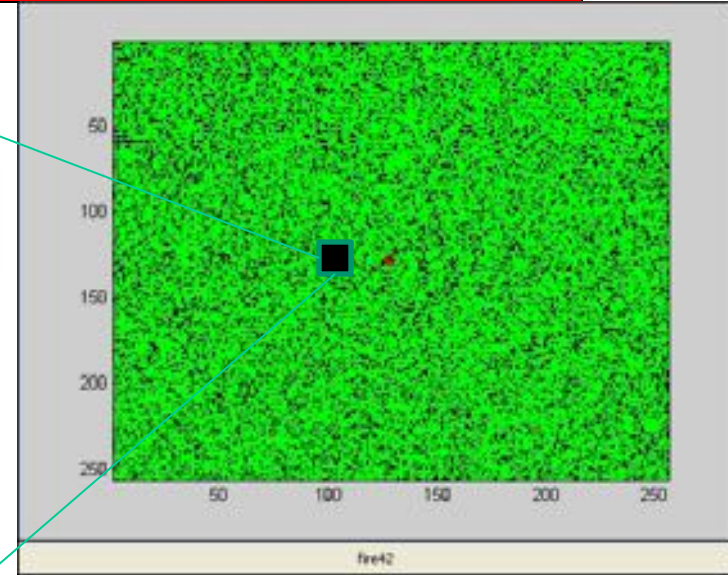
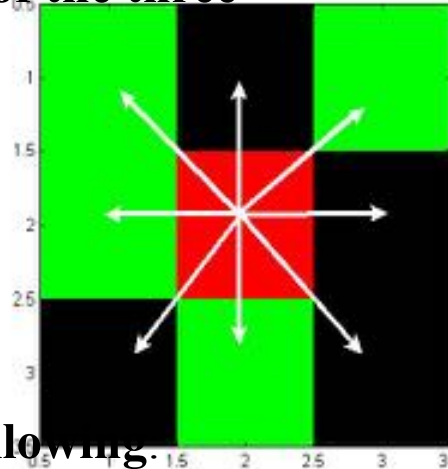
can't predict the emergent behaviour of a system at the macroscale even if one knows exactly the principal laws of the interacting units in the system



Cellular Automata: A simplistic model

A cell can take each time one of the three states:

- 1: Black, empty/burned
- 2: Green, trees.
- 3: Red: Fire



The evolution rules are the following:

- The fire on a site will spread to the trees at its nearest-neighbor sites at the next time step with probability p .
- All trees on fire will burn down and return to empty sites at the next time step.

fire
at time t
at cell (i,j)

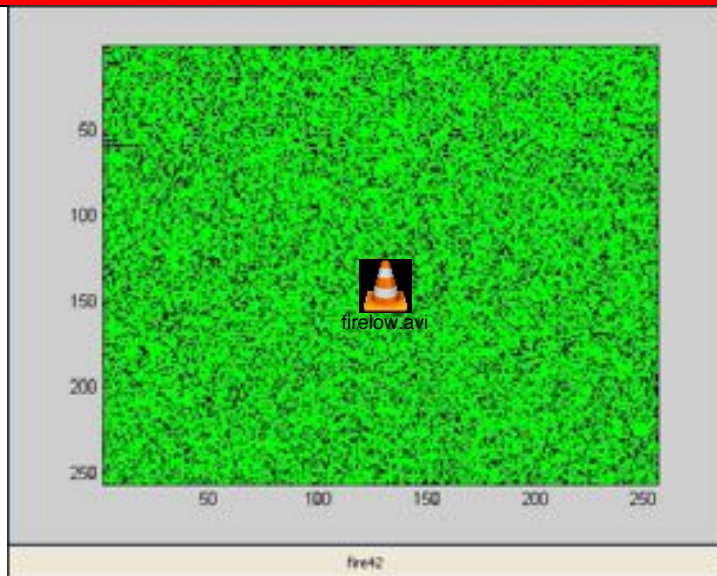
With probability p

fire
at time $t+1$
At neighbor cells

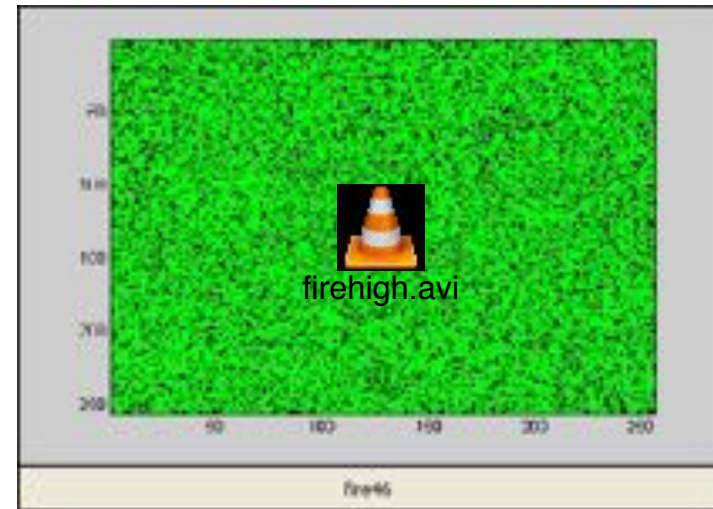
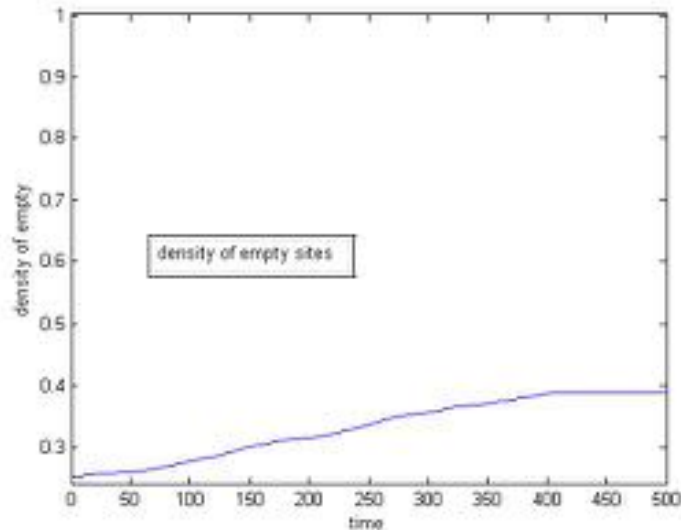
fire
At time t

Empty sites
At time $t+1$

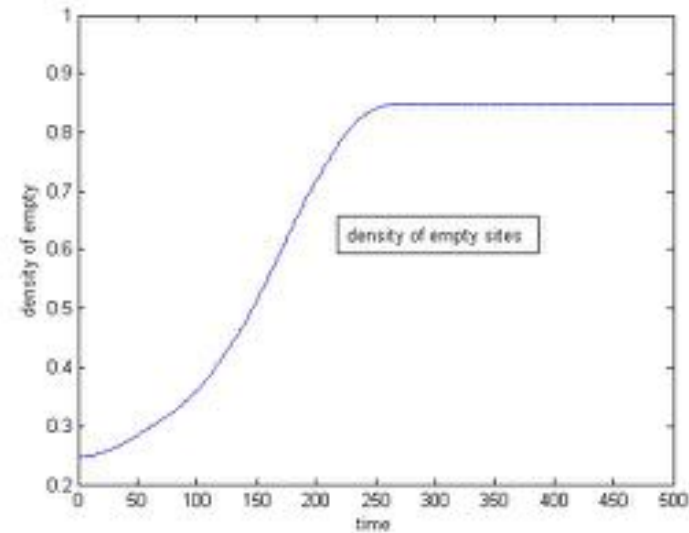
Cellular Automata: Phase transitions



**Probability of Spreading:
42%**



**Probability of Spreading:
44%**



Methodology: Systematic Placement of Fuel Breaks

Our approach to the control of spread of wildland fires makes use of **vegetation cutting in a percentage**, say

d_f of the total number of cells that contain vegetation.

This approach creates a pattern (or zones) of low fuel loading.

A most common, benchmark approach that is used toward to this direction is the **random**, in space, **vegetation cutting**, i.e. the random distribution of empty cells or the reducing of the fuel in the most dense cell

Here motivated by the arsenal of **complex network theory** we propose of a control design approach based on the concept of a specific local statistical measure and in particular the criterion of **Centrality statistic Bonacich criterion**

Methodology: Systematic Placement of Fuel Breaks

The proposed methodology is based on the 2D Cellular automata paradigm

The lattice is now considered as a network, say $G(V, E)$, where

$V = \{v_k\}$, $k = 1, 2, \dots, N$ is the set of vertices -corresponding to the N total cells-, and E is the set of edges, the links between (neighbour) cells

An edge $e_{v_k v_l}$ is defined by $\{v_k, v_l\}$ where $v_k, v_l \in V$ are the neighbour cells

The network is weighted and directed with weights $e_{v_i \rightarrow v_j} = p_b$, where

p_b is the probability that the fire spreads from cell v_i to cell v_j

Methodology: Centrality-based criteria

The BC of a cell k is defined as

$$BC_k = \sum_{l \neq k \neq m} \frac{s_{lm}^k}{s_{lm}}$$

s_{lm}^k is the number of shortest paths between cells l and m passing from cell k **ALL!**

s_{lm} is the number of shortest paths between cells l and m

Bonacich centrality (Bonacich and Lloyd, 2001) which for node k is defined as the k -th component of

$$\mathbf{x} = \left(\mathbf{I} - \frac{\beta}{\lambda_{max}} \mathbf{A} \right)^{-1} \mathbf{e}$$

where \mathbf{e} is a vector of ones and λ_{max} is the largest eigenvalue of \mathbf{A} . **Adjacency Matrix**

Methodology: Centrality-based criteria for the

Distribution of Fuel Breaks

A high value of **centrality** implies that the corresponding cell is connected with other cells by relatively short paths and so is central to the information flow, and therefore the fire spread, in the network (landscape).

Under this view, we rank cells according to their BC values from higher to lower values and we empty the first d_f (percentage) of them.

Hazard Assessment : Hazard Intensity

The hazard intensity R , with respect to the density of fire breaks d_f is defined as:

Density of Fire breaks

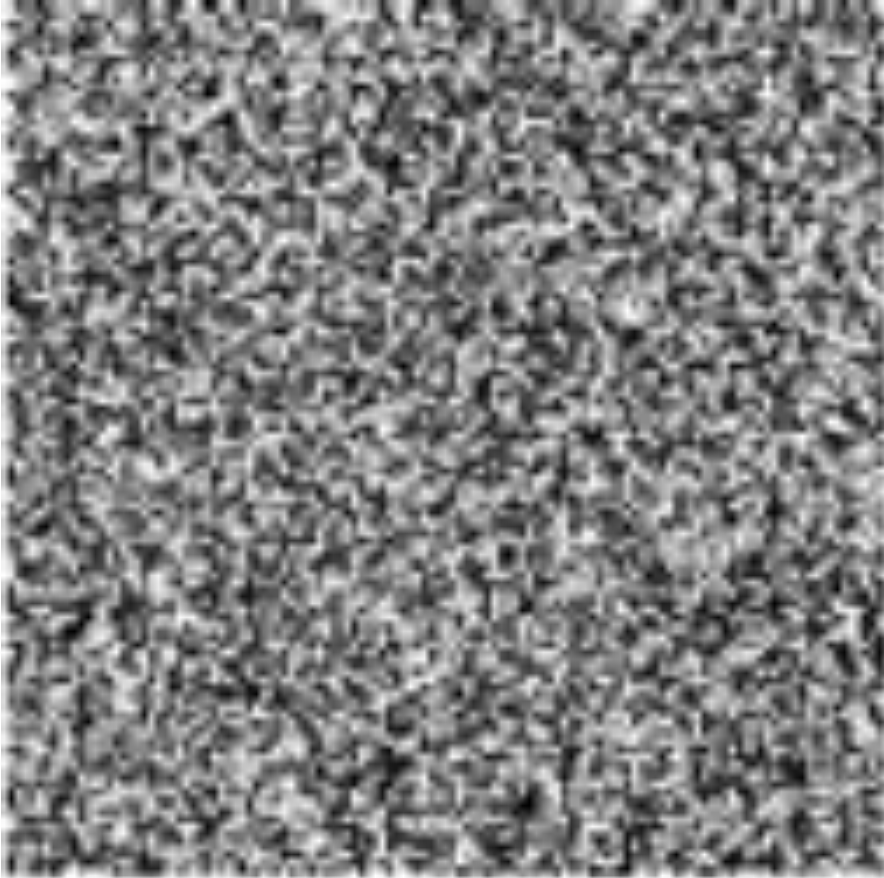
total number of burned nodes

$$R(d_f) = \frac{1}{N_r} \sum_{i=1}^{N_r} \frac{N_b(i)}{N_v}$$

number of simulations
for a given initial condition

total number of nodes
that contain flammable
vegetation

Simulation Results: the artificial forest



$$N_r = 200$$

realizations (ensembles) of randomly generated forest

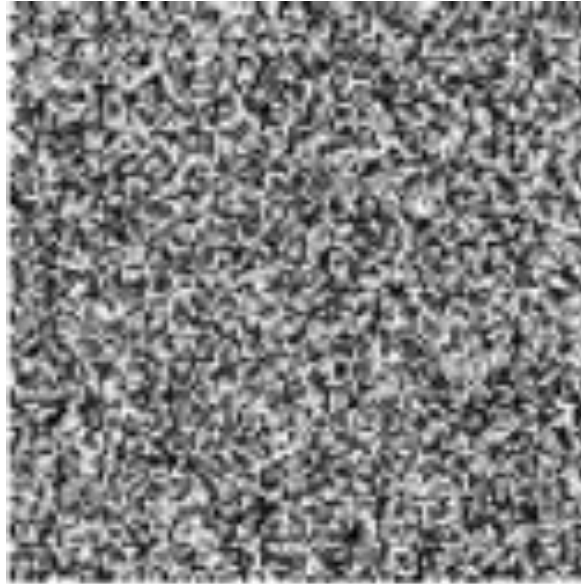
for each one of the realizations we created a corresponding distribution of fire breaks (randomly or BC-based)

and

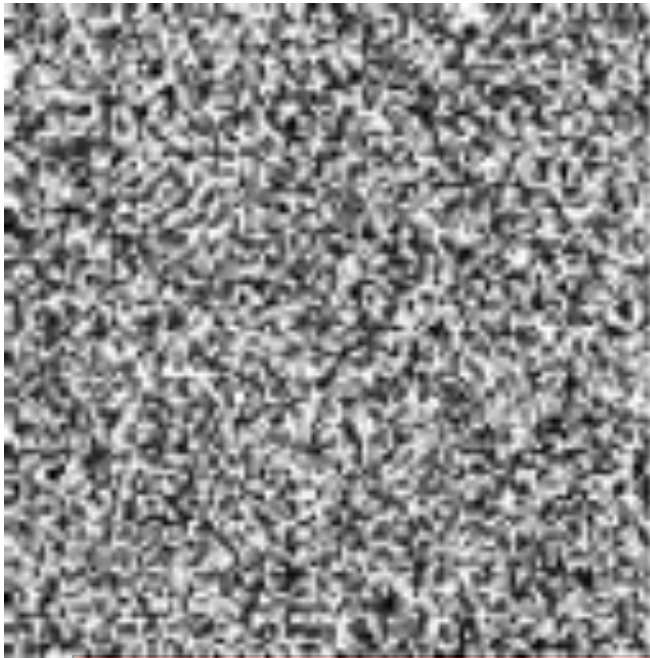
we run the CA model with periodic boundary conditions, until there were no burning cells

Simulation Results: Distribution of fire breaks

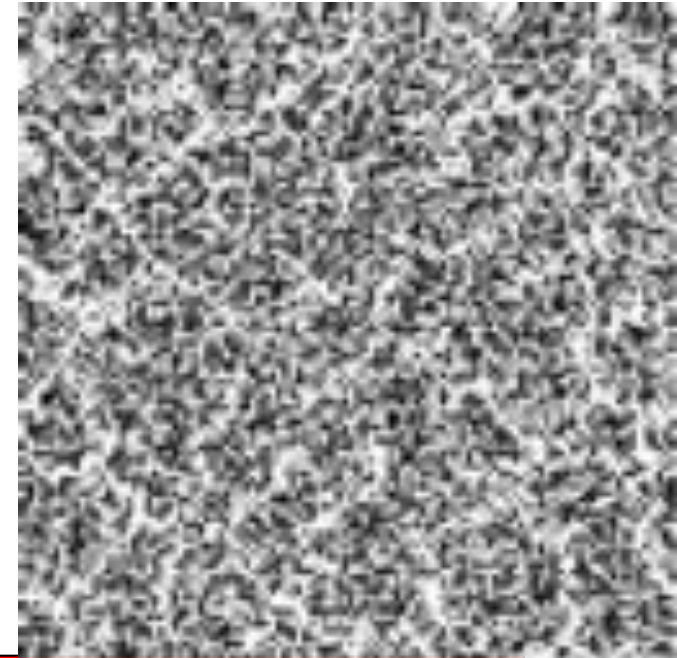
Original Configuration



Random



BC-Based

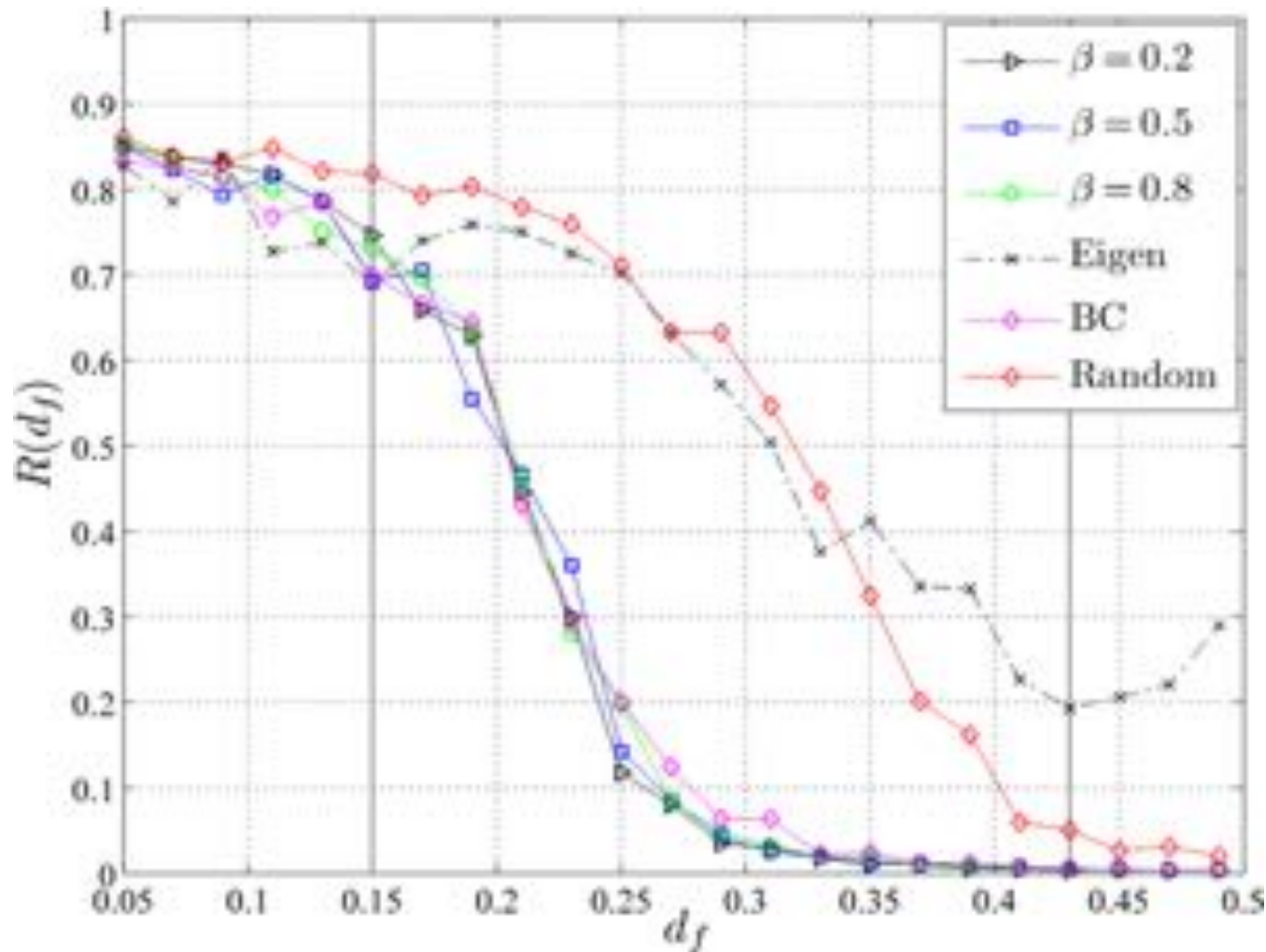


**Cut (10%) of
the total cells**



The simple case of an ensemble of artificial forests.

Average ratio over the realizations, of burned cells with respect to the percentage of fire breaks



Russo L, Russo P, Siettos CI (2016) A Complex Network Theory Approach for the Spatial Distribution of Fire Breaks in Heterogeneous Forest Landscapes for the Control of Wildland Fires. PLOS ONE 11(10): e0163226. <https://doi.org/10.1371/journal.pone.0163226>
<http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0163226>

Our CA-based methodology for wildland fire prediction

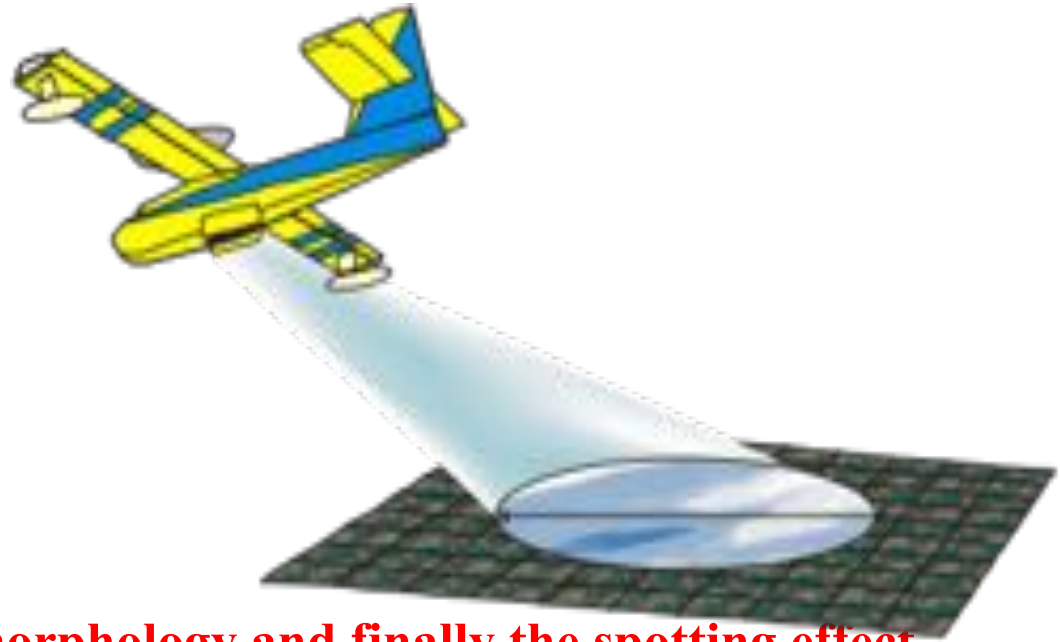
Is Based on GIS data, Meteo-data, types of vegetation

Alexandridis A, Vakalis D., Siettos C.I., Bafas G. V., 2008, A Cellular Automata Model for Forest Fire Spread Prediction: The case of the Wildfire that Swept through Spetses Island in 1990, Applied Mathematics & Computation, 204, 191-201.

Incorporates:

Alexandridis A., Russo L., Vakalis D., Bafas G.V., Siettos C.I., 2011b, Wildland fire spread modelling using cellular automata: Evolution in large-scale spatially heterogeneous environments under fire suppression tactics, International Journal of Wildland Fire 20 (5) ,633-647.

- the type of vegetation,
- the density of vegetation,
- the moisture content of the fuel,
- the height of the vegetation,
- the time-dependent wind field,
- the spatial statistics of the terrain morphology and finally the spotting effect
- Modelling the fire suppression impact

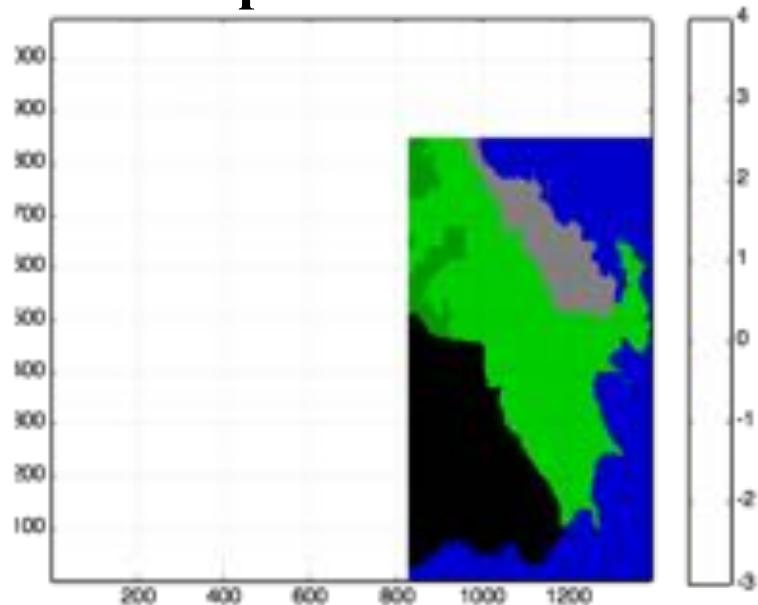


Real Complex Problems: The wildfire of 1990 in

Spetses Island (Greece)

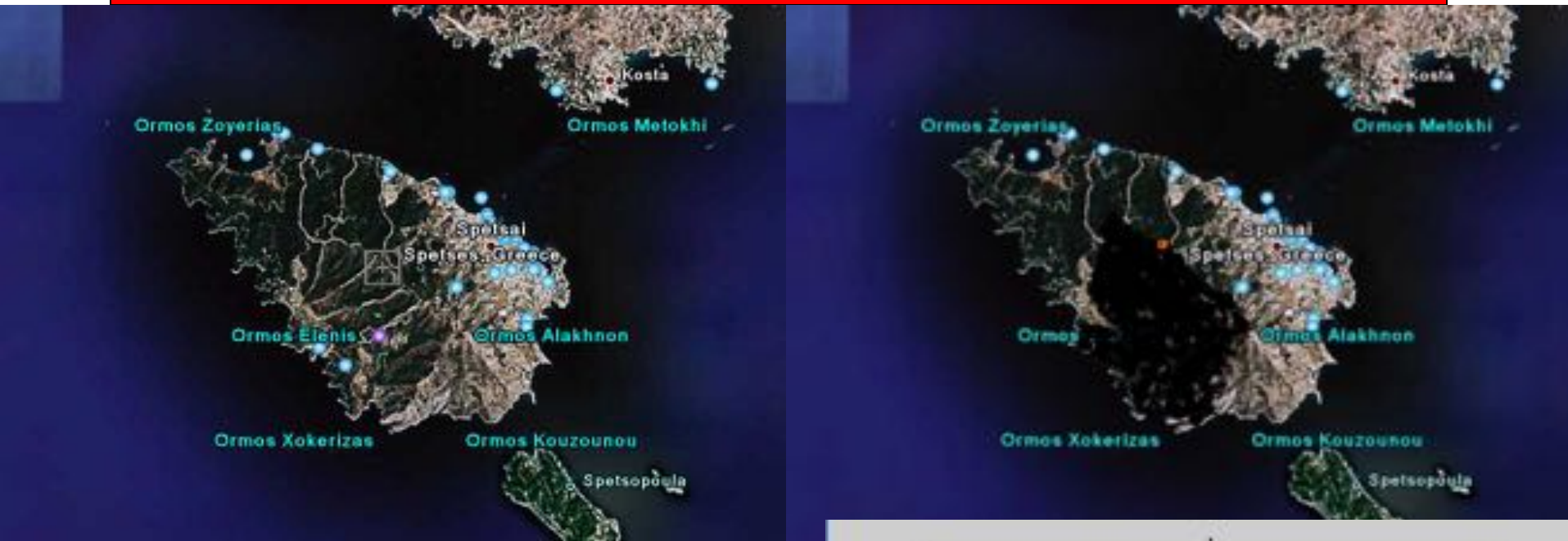
- For our analysis we took as paradigm the case of the wildland fire that occurred in Spetses in August, 1990.
 - The fire ignited near the middle of the island's forest and was quickly spread to the south by moderate to strong north winds.
- The fire was extinguished around 11 hours later, after having burned down a forest area of 8 km², almost the one third of the total area of the island.

Satelite Map of the actual burned Area



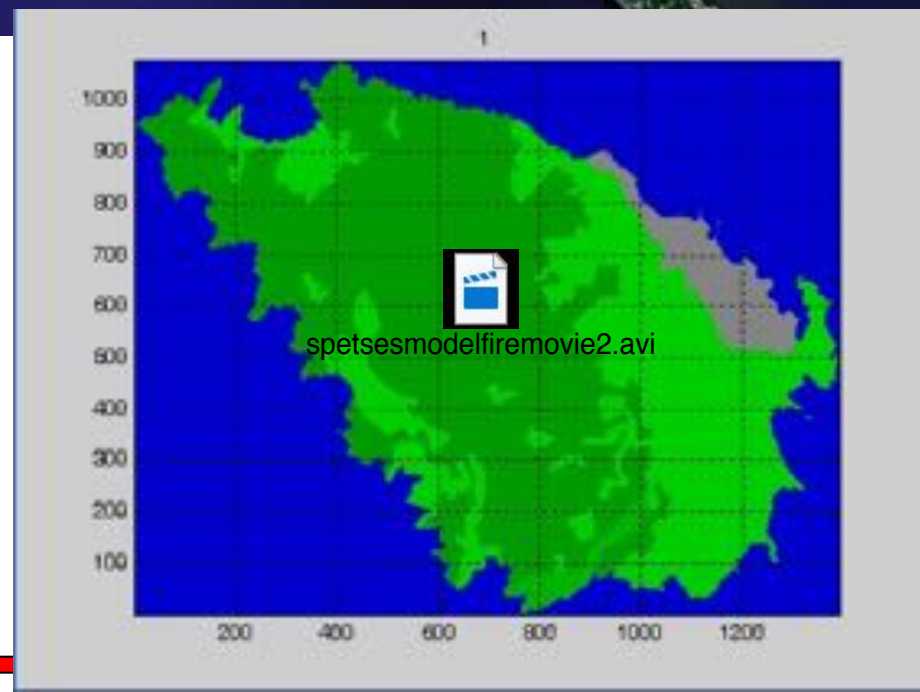
Simulation

Real Complex Problems: Our model



Atomistic/Stochastic Models
Like Cellular Automata
Can! Predict Large & Multiscale
Complex Problems Evolution!

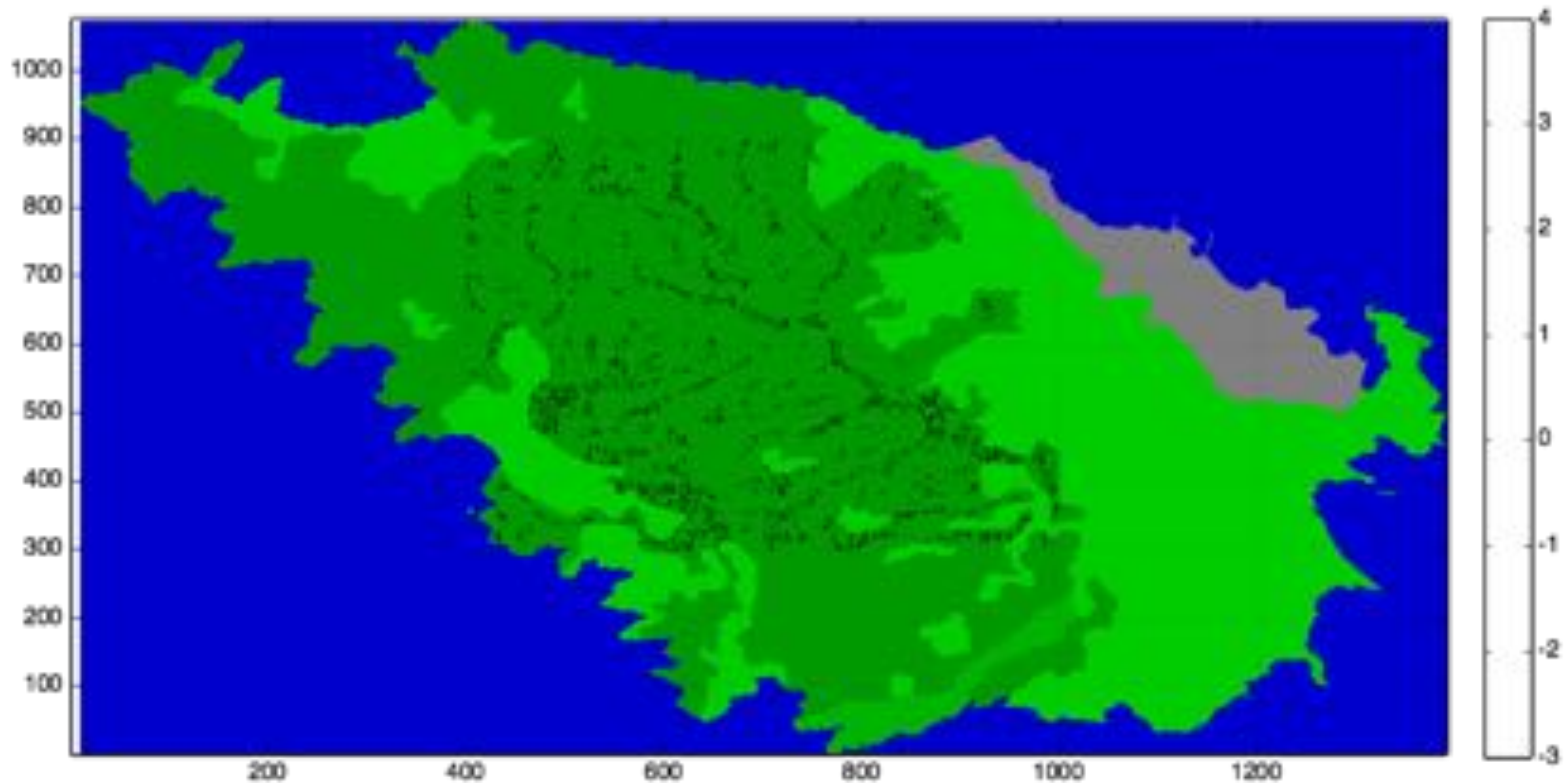
Agents:
Tree = f (Type, Density, Height,
Ground Slope)



Real Complex Problems:

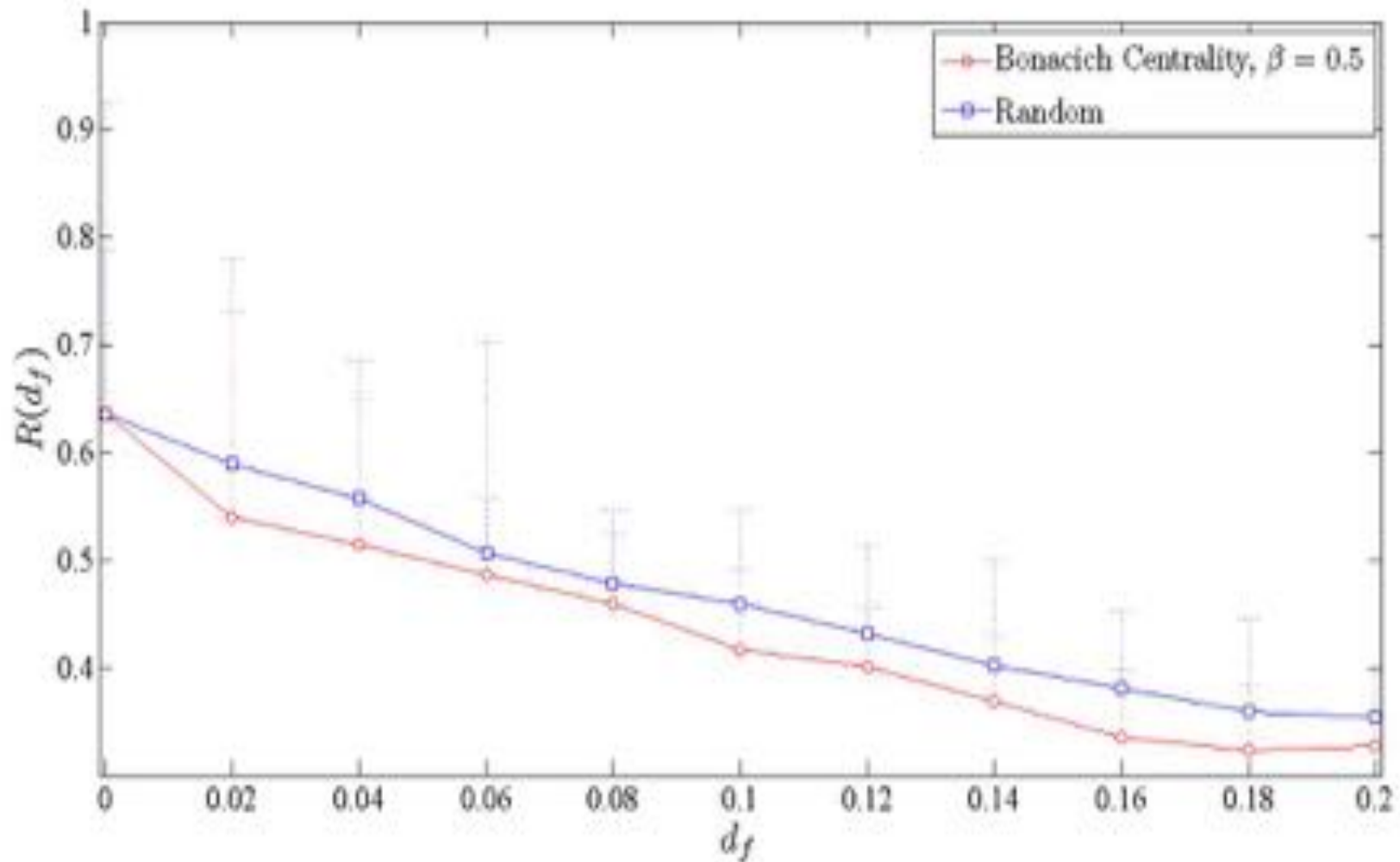
The Distribution of Fire Breaks using the Complex Network Methodology

(10% of total forest)



Real Complex Problems: Spetses Island

Comparison with random distribution of fire breaks



FA stereoscopic image of Rhodes island, Greece (acquired from the NASA Earth Observatory (public domain):
<http://earthobservatory.nasa.gov/>).

The fire occurred on summer 2008 with a total burned area of 13000 ha



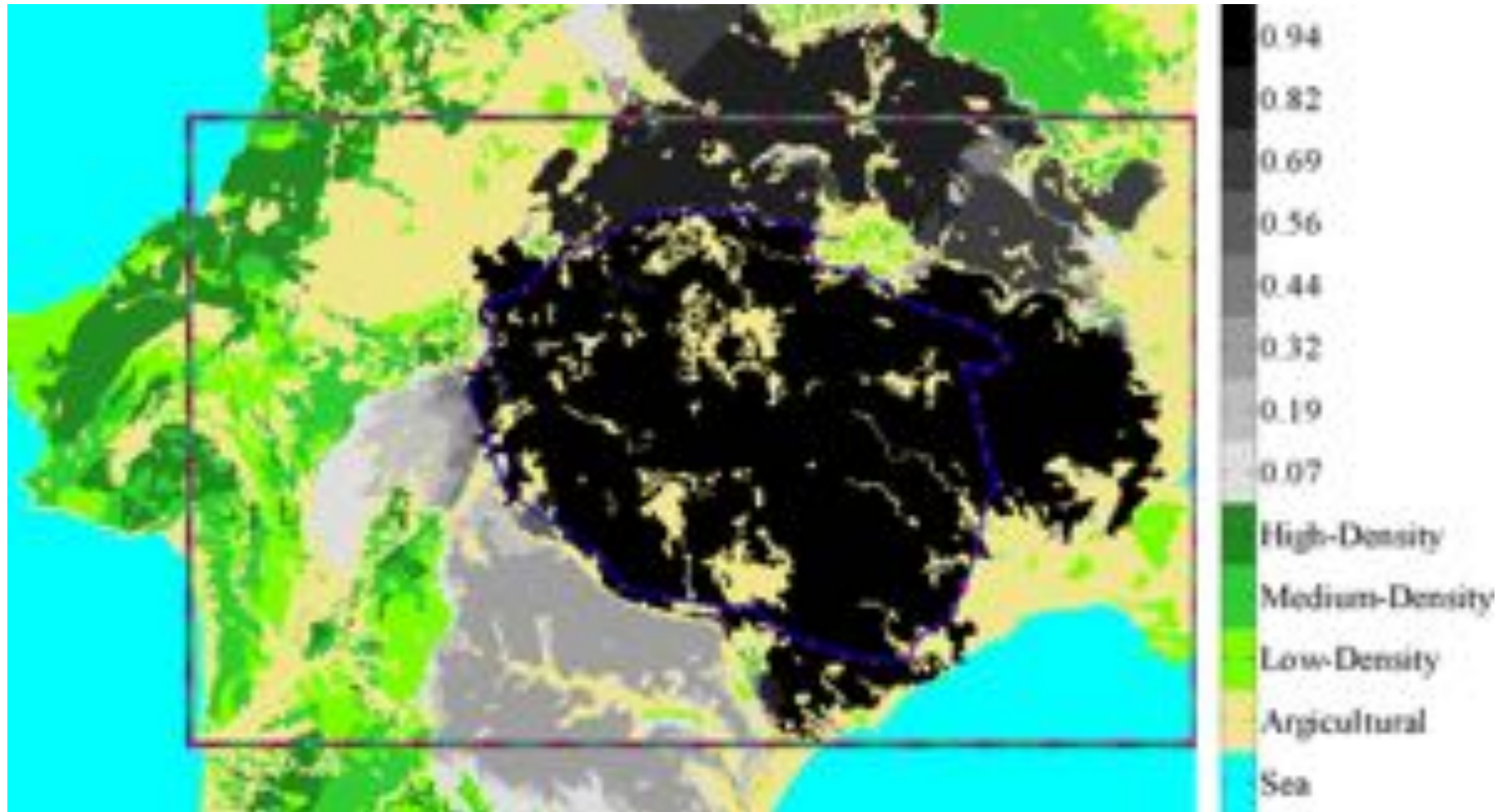
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Map of the vegetation density of the area under study in Rhodes island, Greece as was before the wildfire incident of July 2008.



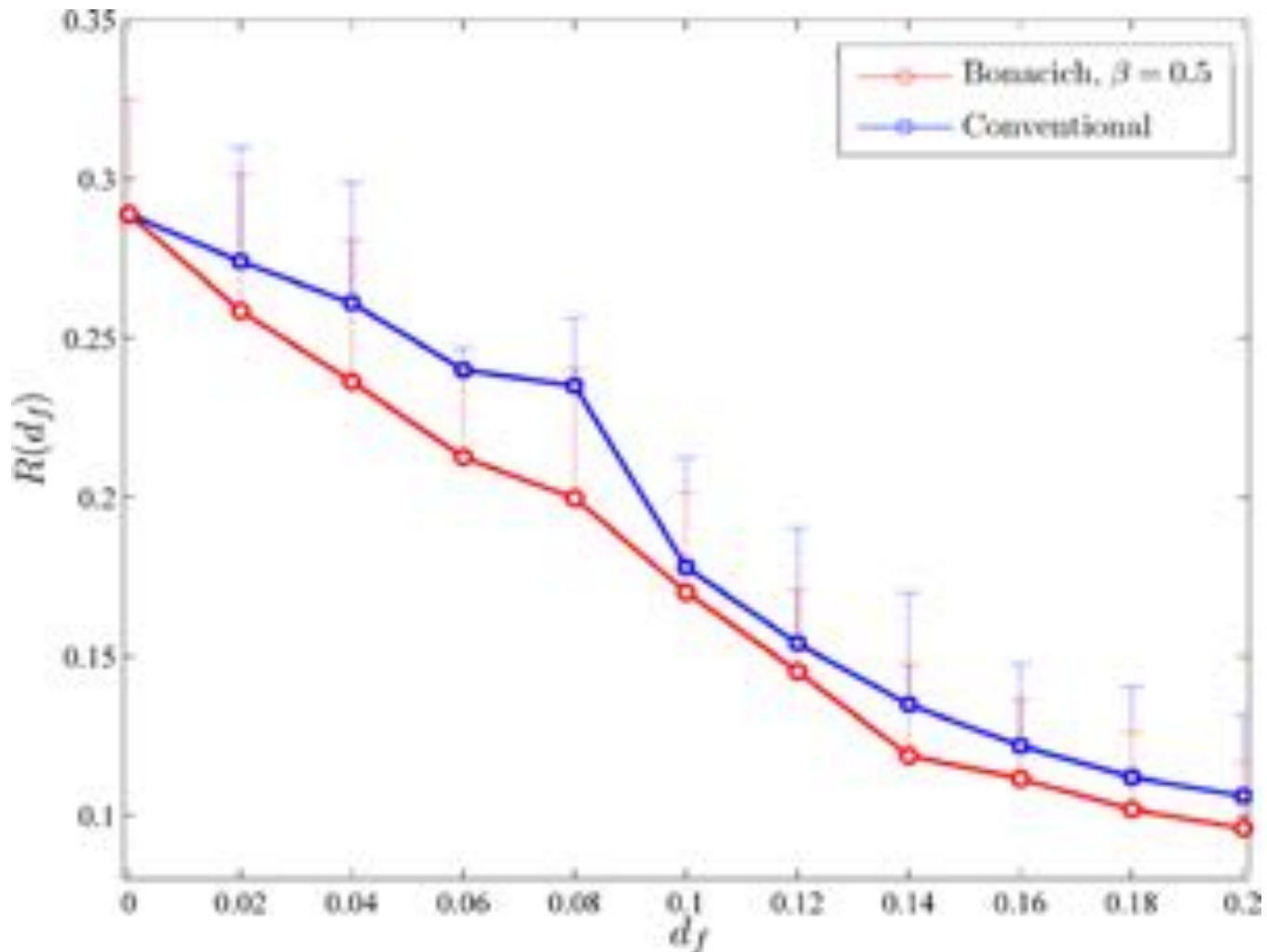
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The “expected” map of relative burning frequencies for the case of Rhodes island, Greece.



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The case of Rhodes island, Greece.



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<http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0163226>

Conclusions

We propose an approach based on a **CA modeling** and **Complex network theory** for the risk assessment and design of fire breaks of forest wildfires.

The proposed approach is based on the BC network statistic that reflects the information flow through the network.

The method outperforms the random and the conventional distribution of fire breaks.

Future work

The design of fire breaks, the test and validation of the CA model in heterogeneous landscapes in Italian regions

Comparison of the CA model with other models (Tiger propagation tool of the Mazzoleni group, Farsite)

Integrate the complex theory criterion with other simulators
