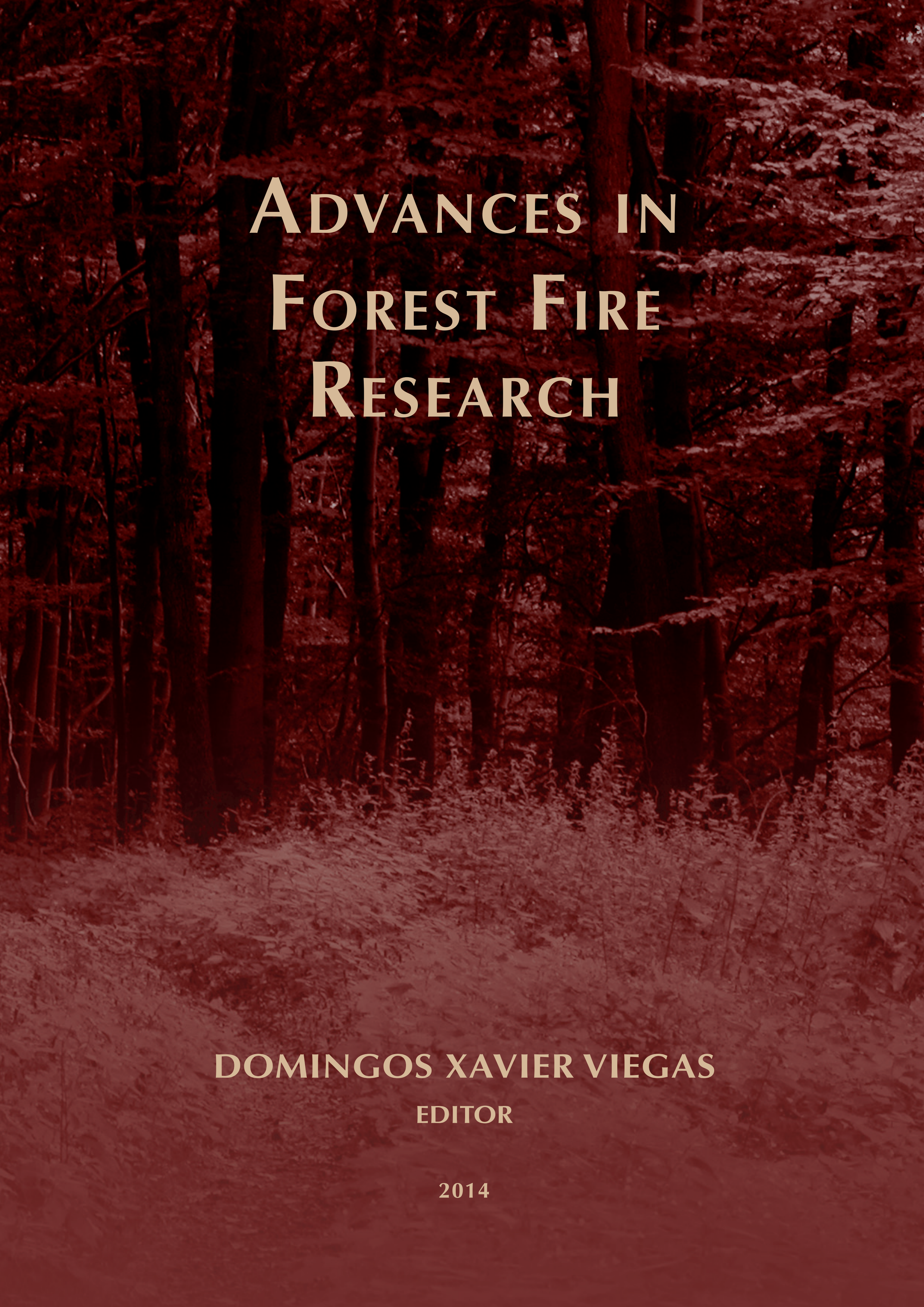

Advances in Forest Fire Research

Domingos Xavier Viegas

Editor

2014

Coupling a meshless front-tracking method with a hybrid model of wildfire spread across heterogeneous landscapes

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Abstract
The objective of the study is to present a method for improving the capability of a semi-physical network model to predict large fire patterns in heterogeneous landscapes. The method, which can be viewed as an Autonomous System, consists in generating an amorphous network by sowing vegetation cells on-the-fly. All the information on fire behavior is contained in the very few digital elevation map pixels close to the fire front, in which fuel items are heated or burning. The method is applied to two distinct scenarios: a no-wind and no-slope academic case and a historical Mediterranean fire that occurred in the South-East of France in 2005. Both cases are discussed in terms of CPU time and memory allocation gains.

Keywords*: front-tracking method, meshless method, network model, large fire, autonomous system, amorphous network*

1. Introduction

As underlined by (Strauss et al., 1989), it is an all too familiar fact that a relatively small number of large fires are responsible for a very high proportion of the total damage. Therefore, simulating the spread of large wildfires, with size up to several tens of kilometers, is a major environmental issue and an active area of research. However this requires the storage and handle of a vast amount of data. As an example, a 10km × 10km landscape, with 60 percent covered by vegetation sites of 2m in diameter, contains approximately 1.5×10^7 sites. Assuming an average number of connections per site of 100, the total number of connections to handle is 1.5×10^9. In order to reduce computational resources, a front-tracking method is here propose.
Another important issue concerns the use of regular lattices (triangular or square lattices) to represent vegetation patterns. However, regular lattices only consider single-class vegetation cover, so they cannot mimic the complexity of natural ecosystems (*e.g.* fuel distribution, polydispersity, mosaic of vegetation types). To overcome this issue, we recommend using an amorphous network.
The combination of the front-tracking method and amorphous network may be viewed as a meshless front-tracking method, hereafter called MFT method.

2. Model overview

Vegetation is here modeled as an amorphous network of cylindrical items where the combustible sites are randomly distributed. A digital elevation model (DEM) represents topography. A weighting procedure on combustible sites is considered in order to account for the effects of ignition and flaming duration (Billaud et al., 2012). The physical model, largely inspired from that of (Koo et al., 2007), is based on the energy balance equation for a control volume of thickness δ located at the top of the cell. δ corresponds to the mean free path of radiation $\delta = 4/\alpha_k\sigma_k$, where α_k is the solid-phase volume fraction, σ_k the surface-to-volume ratio of fine fuel elements. The energy-transfer mechanisms of preheating considered are the radiation coming from the flame $q^{+}_{rad,fl}(i)$ and the embers $q^{+}_{rad,e}(i)$, and $q^{+}_{conv}(i)$ is the wind-driven convection to the top surface of the receptive cell j

$$\sum_{i=1}^{N_{bc}}\begin{bmatrix} q^{+}_{rad,f}(i) + \\ q^{+}_{rad,e}(i) + q^{+}_{conv}(i)\end{bmatrix} = q^{-}_{rad}(j) + \begin{cases} \rho_{WFF}\ c_{p_{WFF}}\ \alpha_k \dfrac{dT(j)}{dt} & T(j) < 373K \\ -\rho_{DFF}\ L_{vap}\alpha_k \dfrac{dFMC(j)}{dt} & T(j) = 373K \\ \rho_{DFF}\ c_{p_{DFF}}\alpha_k \dfrac{dT(j)}{dt} & 373K < T(j) < T_{ign} \end{cases}$$

$q^{-}_{rad}(j)$ is the radiative heat loss to the ambient, T the fuel temperature, ρ and c_p the density and the specific heat of the solid phase. The subscripts DFF or WFF refer to variables evaluated on a dry or wet basis. L_{vap} is the heat of water vaporization and FMC is the fuel moisture content. The ignition delay is the time required for a site under the influence of N_{bc} burning sites to reach a critical temperature T_{ign}. The dynamic of the system clearly depends on the ignition and flame residence times, t_{ign} and t_c. Details can be found in (Billaud et al., 2012).

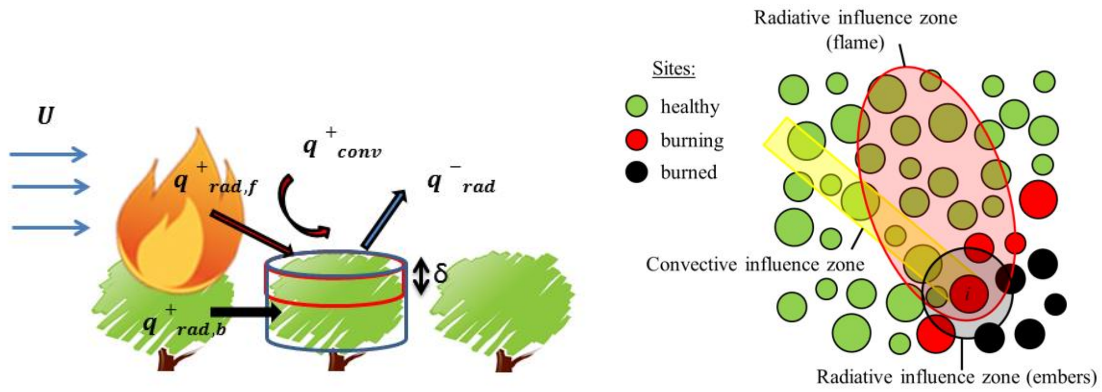

Figure 1. a) Physical problem and b) radiative and convective interaction domains associated to a burning site.

3. Numerical method

The method principle is based on the concept of double indexing: the first is a local indexing of the sites (Holme, 2007), the second is a global indexing of DEM pixels. The main task consists in finding the neighbors of any active site that belongs to a DEM pixel. This can be split into two stages: first, the eight neighboring DEM pixels are identified; second, the sites that belong to these pixels are specifically numbered and stored (Pasquale et al., 2014). If a DEM pixel contains at least one new burning site, the network is updated in order to ensure the continuity of the propagation process. When all the sites of a DEM pixel are burned or too far away from the fire front, the DEM pixel is deallocated.

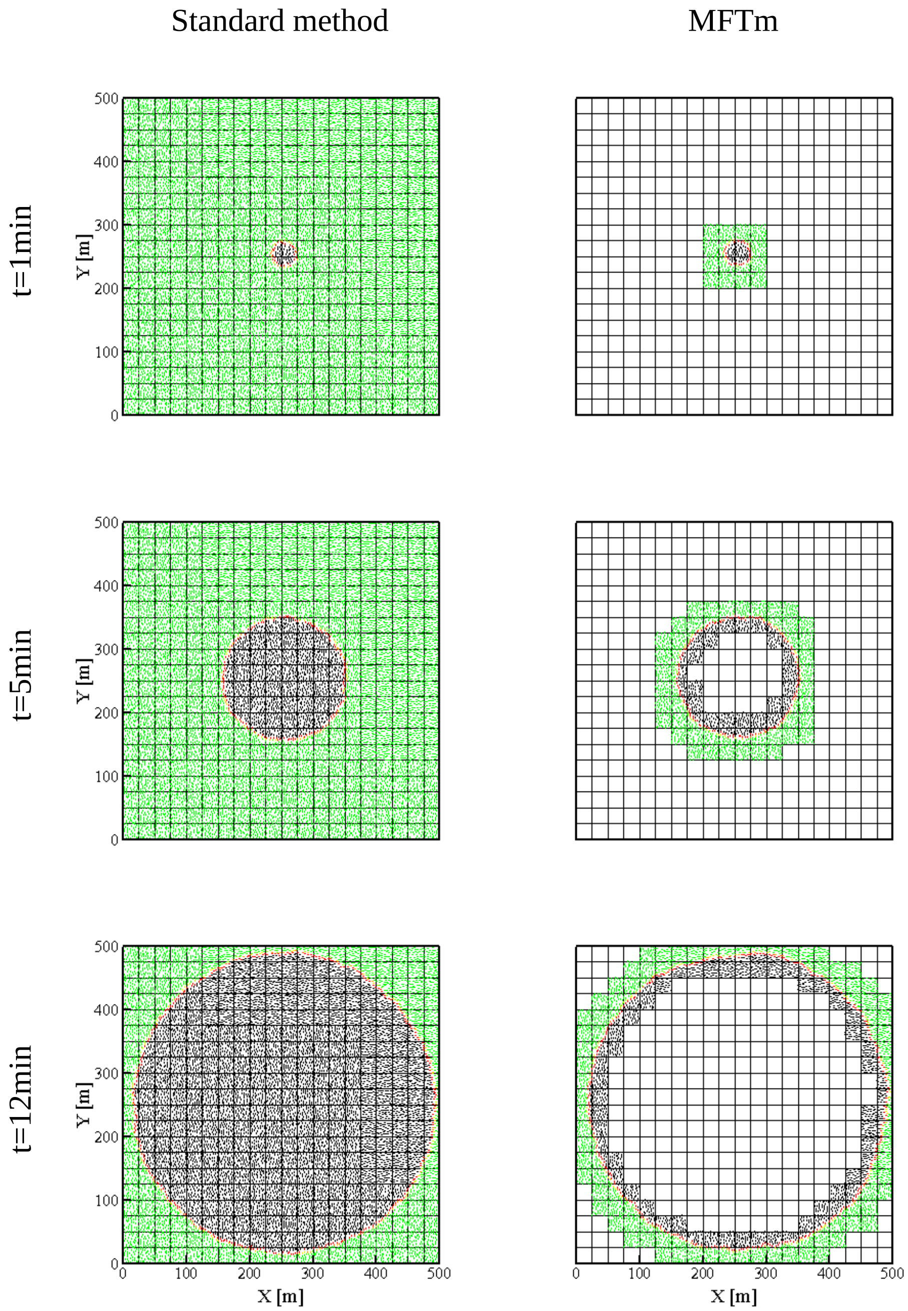

Figure 2. Fire patterns at different instants. Comparison between fire patterns obtained from standard and MFT methods.

3.1. Method validation

In order to demonstrate how such a methodology might work in practice, we consider a 500m×500m monodisperse amorphous network of kermes oak shrubs with a diameter of 2m (Figure 2). The terrain is flat and there is no wind. Ignition occurs in the center of the domain. The vegetation coverage is 0.5. Calculation using the MFT method takes 13s on the Intel Xeon CPU E5-3643 (3.30 GHz, 64 bits), whereas it takes 21s using the standard method, leading to a 38% gain in CPU time. As shown in Figure 2, in the early stages of fire spread (*e.g.* t=1min), only 4% of the network is involved using the MFT method. As time progresses, the memory allocation increases due to an increase of active DEM pixels but remains significantly lower than that of the standard method due to the withdrawing of burned pixels. There are some small discrepancies between the two methods that are due to the stochastic nature of the amorphous network construction.

3.2. Small world effects

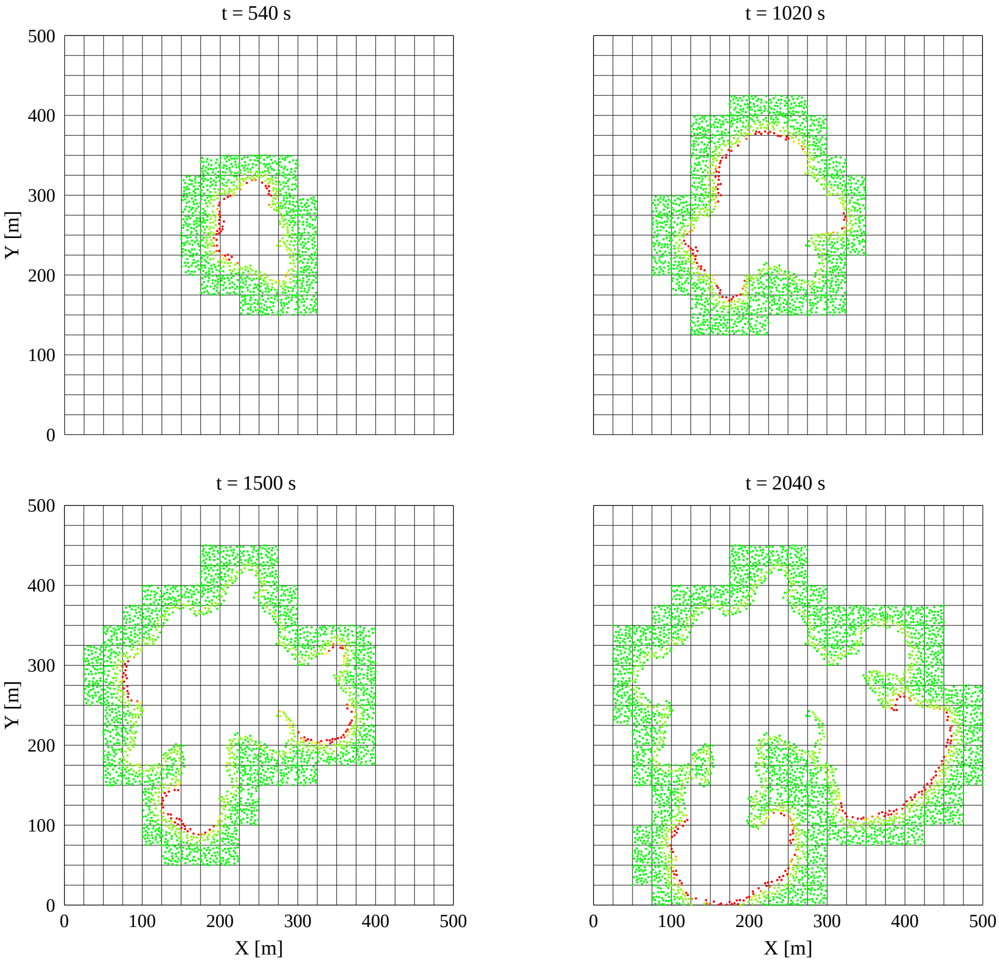

Figure 3. Fire patterns after a) t=540s, b) t=1020s, c) t=1500s and d) 2040s of simulation. The active areas represent about 10%, 17%, 26% and 37% of the total network, respectively.

Here we consider fire spread under the same conditions, except that the vegetation coverage is 0.4. This value is so close to the percolation threshold that small-world effects (clustering, lacunarity, and digitation) occur, as can be observed inFigure 3. Although not shown, similar results are obtained using the standard and MFT methods, with a significant reduction in CPU time and memory allocation.

4. Large scale simulation

The MFT method is now evaluated by simulating an arson fire that occurred at Lançon de Provence, in France, in July 2005. This fire has been extensively studied and documented by the authors (Adou et al., 2010). Geographical data include a digital elevation model and vegetation map at a resolution of 50 m. The dominant species was kermes oak shrub (*Quercus coccifera*). The weather conditions at the time of fire were: an average wind speed of 46km/h at 10 m above the ground level, an average direction of 330° (NNW), and a dry bulb temperature of 30°C. The CFD program Flowstar© was used to calculate local wind direction and speed from the average wind speed, taking into account the effects of topography and surface roughness of the land site. Two ignition points were reported whose geographic coordinates are 5°11’39’’E; 43°36’6’’N and 5°12’21’’E; 43°35’53’’N.

We consider a 10km×7km monodisperse amorphous network of kermes oak shrubs with a diameter of 3m. The vegetation coverage is 0.5.

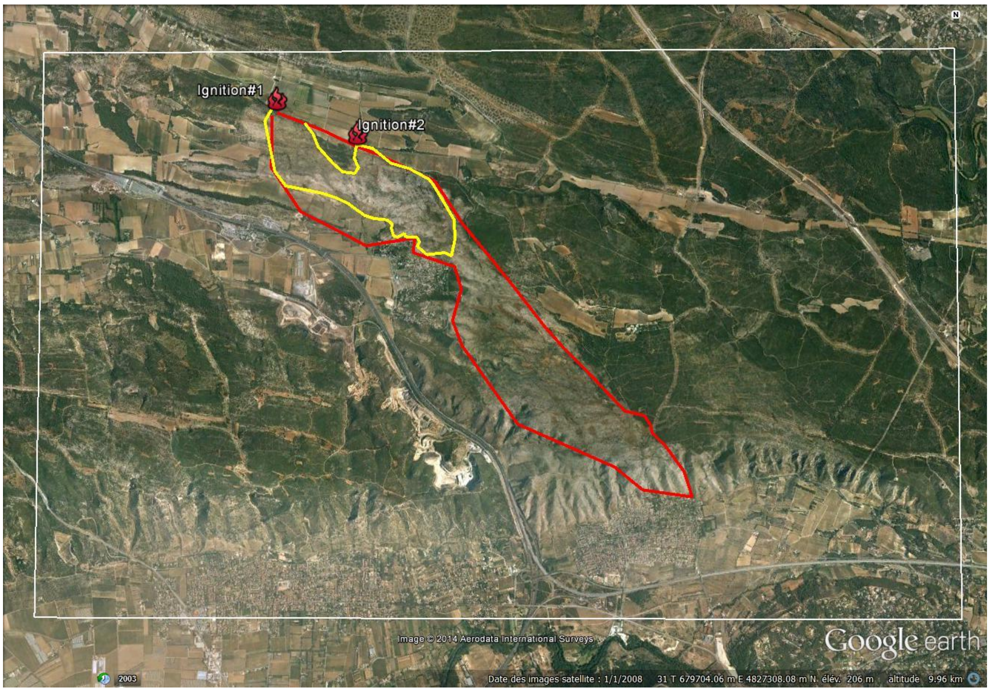

Figure 4. Domain of the study and real fire patterns after t=140min (yellow) and t=300min (red) of propagation.

Contours predicted by the model are compared with field measurements after 140min (Figure 5b) and 300min (Figure 5d) of fire. At t=140min, the average rate of spread is slightly overestimated which leads to a more advanced position of the head fire front. This may be due to time variations in wind properties which are averaged in the model. Integration of time-dependent meteorological conditions is possible but such information is unavailable for the present case. At t=300min, the agreement remains effective. Discrepancies between predicted and real contours, in particular in the lateral extension of the fire, are mainly due to the fire crew intervention which was not introduced into the model because of lack of information on the location and nature of the fire-fighting task force deployed. It may be noted that the model can easily take into account the action of fire fighters by rendering soaked vegetation inactive.

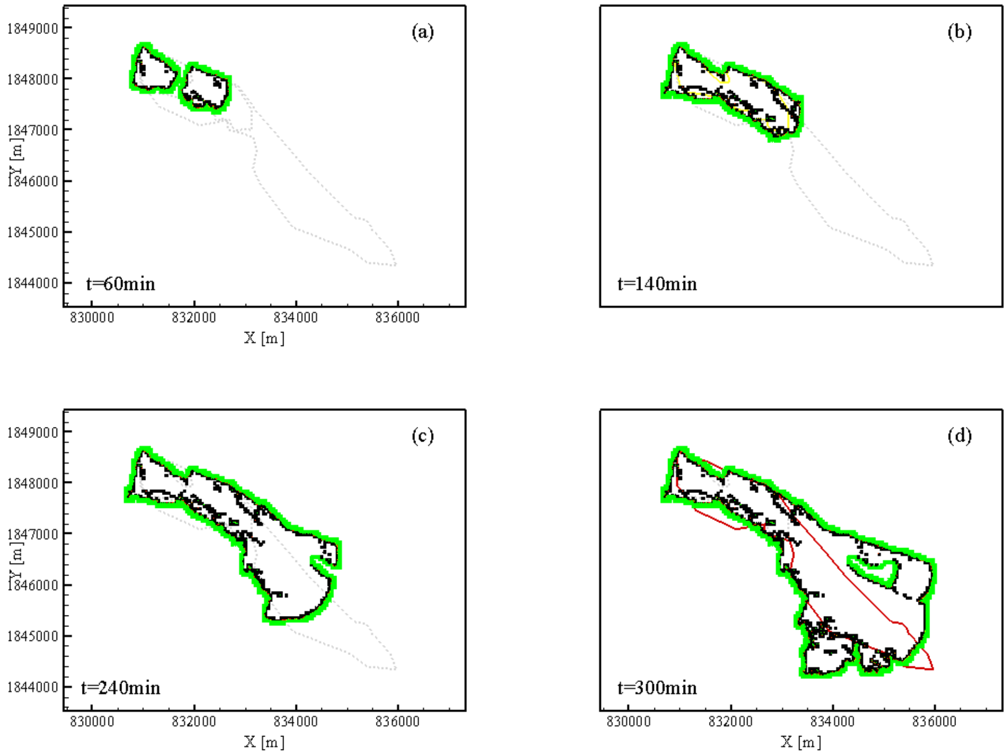

Figure 5. Fire patterns after a) t=60min, b) t=140min, c) t=240min and d) t=300min of simulation. a) and c) are compared with real fire pattern.

As mentioned before, two ignition points were reported for this fire. At t=60min (Figure 5a), the two independent fire fronts interact and merge into a single one. This shows the capability of the method to handle phenomena frequently observed in wildland fire propagation in complex terrains, such as splitting and coalescence of fire fronts. The model can thus be used to evaluate the efficiency of counterfire.

The overall CPU time gains are substantial when using the MFT method as it gives, in the present case, a 450% overall performance gain compared to the standard method. This gain is mainly due to the memory allocation/deallocation strategy, reducing memory allocation and the search space of connections between sites.

5. Conclusion

A method for improving the capability of a semi-physical network model is used to simulate large fire patterns in heterogeneous landscapes. The basic concepts of the model are recalled and the last improvements, including the use of an amorphous network and the front-tracking method, are presented. The strengths of the meshless front-tracking method are illustrated through an academic case. Method validation is achieved to an acceptable degree through comparison of results with data from a well-documented historical Mediterranean fire. The performance of the method is evaluated in terms of computational resources.

6. Acknowledgments

MDG gratefully acknowledges the financial support from NOVELTIS and ANRT (CIFRE/ANRT contract n°566/2013).

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