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A simulation software of forest fires based on two-level cellular automata

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ABSTRACT: A software system for the simulation of small-scale fires in Mediterranean landscapes is presented. The software uses a model of fire spreading deriving from the classical Rothermel's Rate-Of-Spread theory. It exports this method, based on American forests peculiarities, using Valette's classes of inflammability, tested for Mediterranean coverage. The forest is modeled as a two-layer cellular automata: the upper layer representing the crowns of the trees and the lower one the surface coverage. Slope, air temperature and moisture data are introduced through coefficients like in Rothermel's model; wind effects are based on Alexander's ellipse theory. The software has been developed to supply fire-operators with a real-time tool: the simulator automatically retrieves GIS coverage and digital terrain model data, shows on the screen all the active operators by GPS positioning, saves and re-runs any step of the simulation to test different fire management actions.

1 INTRODUCTION

Forest fires are one of the most important source of environmental degradation in most Mediterranean countries and cause more and more significant economic and social damages to population. There are basically two reasons for such an increase: the first is the raising difficulty to find an equilibrium between urban and non-urban environments. The pressure for using more land for recreation, living, building infrastructures exposes forests and all non urbanized environments to an increasing level of threat to their normal development. The second is the progressive abandoning of mountainous areas in favour of living elsewhere. This implies a diminished surveillance and maintenance of woods which may easier suffer destructive fires. This situation is well described by the data of the Italian Forest Service (www.corpoforestale.it): more than two third of the fires (see fig. 1) are fraudulent or due to negligence.

Another important characteristic of Mediterranean countries is the great variability of the landscapes. In contrast to the substantial homogeneity of American forests covering large areas with moderate variations in altimetry, the situation of south European countries is characterized by complex topography, variety in soil coverage, and great seasonal oscillation in fuel characteristics (Hakkila, 1989).

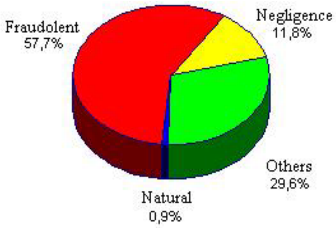

Figure1. Forest fire causes in Italy in 2001.

In Italy, for example, seasonal fuel and environmental conditions produce different risks of fire according to the season in different areas: winter is droughty in the north, where, despite the relatively low temperature, the dry vegetation can rapidly burn; while summer is the most dangerous period in the south, due to the high temperature and the lack of water (see fig. 2).

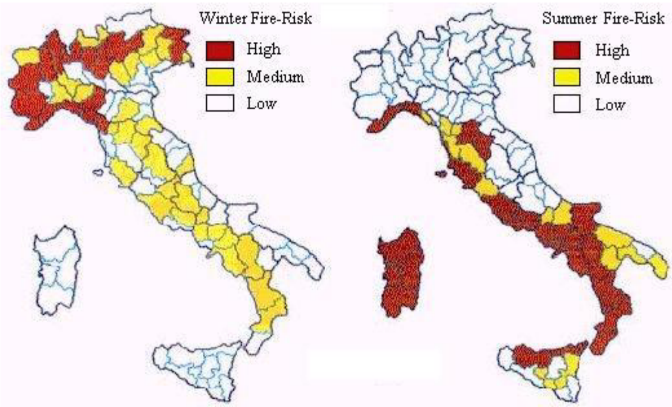

Figure 2. Seasonal fire risk in Italy in year 2000.

To face such a dangerous and extended phenomenon, besides a well-known set of structural interventions, other non structural measures like getting better prediction systems, and assuring the quality of all data, i.e. their availability, completeness, and updating may play a relevant role. Among these measures, the implementation of a dedicated software with the ability of fast data retrieval and realistic and rapid simulation of the spatial dynamics of forest fires can certainly contribute to improve the overall fire protection and fighting system. This is particularly true in the crowded regions of Northern Italy, where forest areas are very limited and the main problem is to rapidly reach and fight fires, that can rarely attain large dimensions.

Cellular automata, as is well known, provide a practical and flexible framework for the simulation of spatially distributed phenomena (Spezzano et al., 1999; Cecchini et al., 1999) and have already been used in the analysis of fire spreading. The literature is already rich of software packages demonstrating the joint use of cellular automata and GIS capabilities: e.g., Dynafire (Kalabokidis, 1991), FireGis (Gonçalves, 1994), Firestation (Lopes et al., 2002).

The software package described in the paper is also based on the cellular automata paradigm (Codd, 1968), but implements a 3-D version, thus more accurately representing the different behaviors of the surface covering and of the tree crowns. More specifically, the software runs on a standard PC under Microsoft Windows with the addition of Map Object package (www.esri.com) to manipulate geographical data and has both GIS and simulation features. It allows standard GIS operations like visualization of different layers, zooming and panning, but also automatically ex-

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tracts from regional maps land coverage and elevation patterns in the region of interest. Then, as it will explained in the following three sections, it simulates fire spreading taking into account the peculiarities of the surface and crown layers. Finally, its ability to assist local authorities in managing different resources to fight an active fire will be shown in section 5.

2 A TWO-LAYER MODEL

The fire spread model implemented in the project is based on cellular automata theory. The area under study is represented as a square grid of user selected dimensions in which each square cell, the elementary automaton, may assume four different states (normal, warming, burning, burned/inactive). The peculiarity of such a model is the co-existence of two parallel layers: the upper ones represents the tree crowns, the lower one the surface coverage (fig. 3).

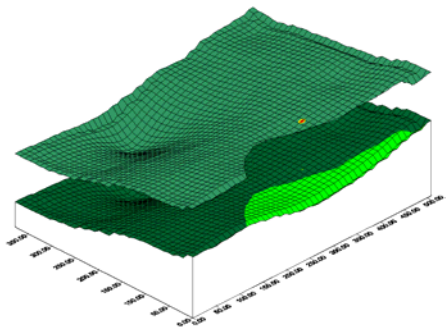

Figure 3. Two-layer model example.

Cellular automata evolve through interaction between elementary automata which exchange information about their own condition. The interaction is local because only a certain group of cells of the space extents its influence on a cell; during every step, all the cells update their state in synchronous mode. The information transferred in this case is the thermal energy emitted by fire; cells susceptible of influencing a given cell are called neighborhood: they are ten (see fig.4) and include the cell itself, the confining eight of the same layer, and the homologous of the other layer.

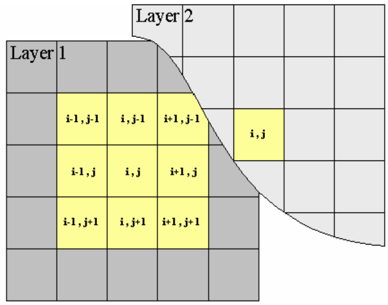

Figure 4 Neighborhood of (i,j) cell.

Each cell is considered either burnable or not-burnable. In the first case, the cell can be *normal*, *accumulating energy*, *burning* or *burned*; in the second case, the cell is *inert* and it does not participate in the heat transfer process. Cell representing vegetation are burnable: a type of coverage has to be identified for that area and is approximated to homogeneous and monotype for every cell which represent the area. The evolution of a burnable cell hit by heat, is defined by the comparison of the energy accumulated in the cell and certain fixed values called *threshold*, typical of the kind of vegetation present in that cell. The scheme of the complete cell update function is shown in fig. 5.

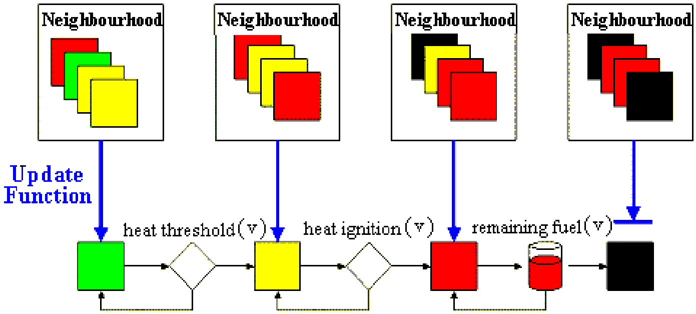

Figure 5. Update function of the elementary automaton.

The update function accounts for the heat flux entering every cell, from the respective neighborhood; if the entity of the energy accumulated in the cell (*i,j*) exceeds the heat threshold $T_h(v)$ (a property of the particular vegetation coverage, *v*), the cell changes its the state from *normal* to *accumulation of energy*. At the reaching of the next ignition threshold $T_i(v)$ (again a property of the vegetation *v* of the cell), the cell starts to burn the fuel available at that time, $F_{ij}^t(v)$, and remains in the *burning* state till $F_{ij}^t(v)=0$. The burned cell behaves, in the following steps, like an *inert* cell, that is, it cannot transfer heat any more. The local update function can thus be written as (*sign*(*x*) is 0 for *x*=0, and 1 elsewhere):

$$H_{ij}^{t+1} = T \cdot U \cdot \left[H_{ij}^t + A\left(H^t\right) + B\left(H^t\right) + C\left(H^t\right)\right] \cdot sign(F_{ij}^t(v)) \tag{1}$$

where the heat content *H* of cell (*i,j*) at *t+1* depends on environmental conditions (air moisture, *U*, and temperature, *T*) and on the state of the respective neighborhood (marked in yellow in fig. 6) at step *t*, with the following rules:

$$\begin{aligned} A\left(H^t\right) &= \alpha \cdot \left(NN \cdot b \cdot H_{ij-1}^t + EE \cdot d \cdot H_{i+1j}^t + SS \cdot f \cdot H_{ij+1}^t + WW \cdot h \cdot H_{i-1j}^t\right) \\ B\left(H^t\right) &= \beta \cdot \left(NW \cdot a \cdot H_{ij-1}^t + NE \cdot c \cdot H_{i+1j-1}^t + SE \cdot e \cdot H_{i+1j+1}^t + SW \cdot g \cdot H_{i-1j+1}^t\right) \\ C\left(H^t\right) &= \gamma(w) \cdot \overline{H}_{ij}^t \end{aligned} \tag{2}$$

where $\overline{H}_{ij}^t$ represents the heat accumulated in the correspondent cell of the opposite layer and the parameter $\gamma(w)$, which translates the mutual influence of the two layers(bioenergy.ornl.gov), is a function of the wind speed *w*.

The heat content is then mapped to the state of each cell with the following rules:

$$F_{ij}^t(v) = 0 \Rightarrow inert$$

$$F_{ij}^t(v) > 0,\ 0 \le H_{ij}^t \le T_h(v) \Rightarrow normal$$

$$F_{ij}^t(v) > 0,\ T_h(v) < H_{ij}^t \le T_i(v) \Rightarrow accumulation$$

$$F_{ij}^t(v) > 0,\ T_i(v) < H_{ij}^t \Rightarrow burning, F_{ij}^{t+1}(v) = F_{ij}^t(v) - \Delta$$

where Δ is the amount of fuel burned in the unit time step.

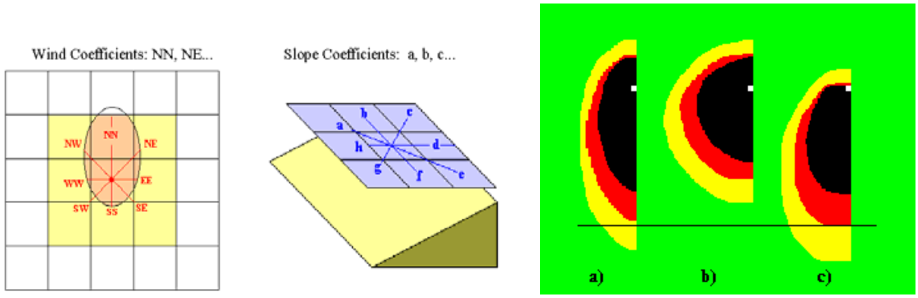

Figure 6. Wind (a) and slope (b) coefficients and their separate and joint (c) effect on fire shape.

The first two coefficients, α and β, are set to warrant a circular fire spreading in homogeneous and isotropic conditions; the second group of coefficients (NN, NE,…) translates the wind effect on the eccentricity of the ellipse (Alexander, 1985) of the burning line (fig. 6, left); and the third set (a,b,c,…) controls the influence of terrain slope on the spreading of fire (fig. 6, middle).

The model as a whole follows the well-known formulation by Rothermel (1972). Experimental data for its calibration are difficult to find, but can be in part derived from the literature (table 1 shows for instance some characteristics of the Mediterranean trees measured by Valette, 1990).

Table 1. Threshold values and normal fuel content for sample Mediterranean vegetation (from Valette, 1990)

Classification (v)	Layer (Surface/Crown)	Heating threshold $T_h(v)$	Ignition threshold $T_i(v)$	Fuel reserve $F(v)$
Pastures	S	0.02	7	9
Wood growing	S-C	0.12	12	13
Resinous forest	S-C	0.06	15	19
Broad.leaved forest	S-C	0.12	12	16
Coppice forest	S-C	0.12	12	16
Grass	S	0.02	7	9
Non-burnable	S	-	-	-

The calibration also derives from known facts about fire spatial dynamics. For instance, as already mentioned, it is well known that, whatever the initial shape, the fire should assume a circular form onto homogeneous and isotropic patterns; and that both wind and slope cause the fire to produce an elliptical shape (as shown in figure 6).

3 EFFECTS OF ENVIRONMENTAL VARIABLES

Fixing all environmental conditions except one, the behavior of the model in dependence of that variable can be checked. For instance, assuming the absence of wind and a homogeneous land coverage represented by a single layer (e.g., grass), one can determine the fire dynamics due to differences in elevation. A sample situation is shown in fig. 7, where the ignition has been placed near a deep hollow in the ground (see the contour map on the left side): the fire proceeds much slower toward its bottom than in other directions (right side of fig. 7).

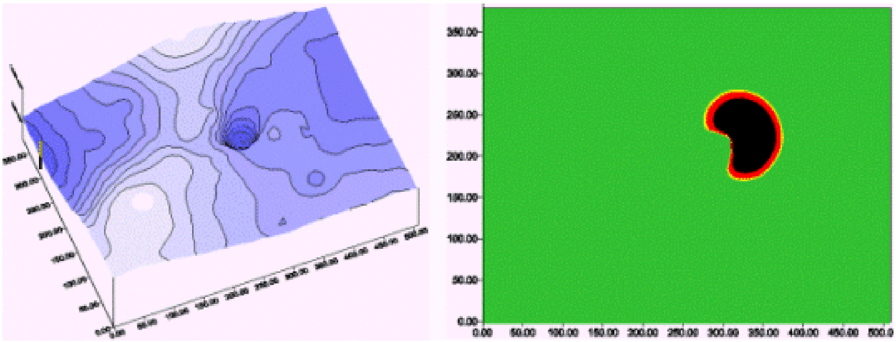

Figure 7. Effect of complex topography on fire spreading.

A classical action to fight fire spreading is a reduction of available fuel (Van Wagtendonk, 1998) or a complete cut of the vegetation in a strip of land (fire line), to create a discontinuity of the fuel (Calabri, 1984). The effect of this action is shown in fig. 8. Assuming a homogeneous coverage except for fire lines, one can see that the fire develops in its standard round shape, until it hits the discontinuities. Here, additional spreading is blocked, but, if the fire lines do not constitute a continuous perimeter, fire can attack the fuel between them at a slower speed, and eventually pass the barrier and start developing as if burning cells constitute new ignition points. This effect is clearly visible on the right side of fig. 8 and has been already pointed out by Finney (1994), who suggested its similarity with the principle of wave propagation by Huygens-Fresnel.

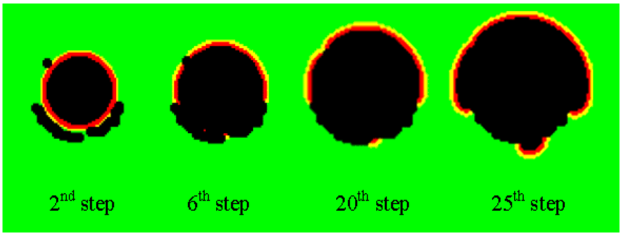

Figure 8. Effect of fire lines in a flat grass coverage.

4 INTERACTION BETWEEN LAYERS

The capacity of the model to accurately reproduce small scale phenomena better emerges when considering the existence of two layers, as, for instance, in hardwood forests.

The simulation in fig. 9 assumes a flat terrain, a portion of which is covered by grass and the remaining part by trees. A road crosses the area, but it is seen only in the surface layer (left side of the figure) since the tree crowns (right side) are supposed to be more dense and to cover the road. Wind is absent.

A fire starting in the grass develops in the standard way till it hits the road on one side and the trees on the other. The road forbid a further propagation in that direction, while the fire continues within the trees, even if with at a reduced rate of spread (fig. 9, step 35). The crowns are not immediately attacked, but, after a while, the heat raising from the surface set also them to fire (fig. 9, step 45). At this point, the fire spreads between the crowns, crosses the road, re-ignite the surface at the opposite side, for the heat spread by the upper layer, and starts propagating again also in the grass. In a single layer approach, the fire has no possibility to exceed the non-burnable area, and a kind of discontinuity like the road becomes an insurmountable obstacle, unless the wind is sup-

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posed to transport burning material on the other side of the discontinuity. Here, on the contrary, the fire slows down, but it is not definitely stopped.

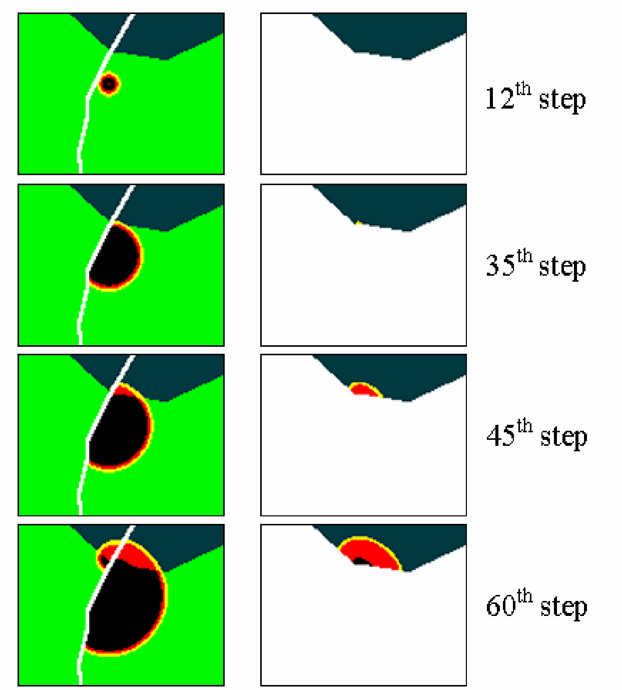

Figure 9. Crossing of a country road. Surface layer on the left and crown layer on the right.

The two-layer modelling better controls the behavior of fuel in accordance with its distribution in the scenery and the different effects of the wind on it. A simulation in a flat, homogeneous area (figg. 10-12) can pinpoint this aspect.

At the beginning, with a strong wind blowing from northwest (see arrow in fig. 10), the ignition of a fire on the surface or on the crowns does not immediately propagate to the other layer (see 1 and 3 in fig. 10, which are respectively on the surface and on the crowns of a uniform tree area, while 2 starts from both layers). Later, the falling of burning material propagates the crown fire to the surface, but the wind, which produces a strong eccentricity of the elliptical shape of spreading, along its direction, prevents sufficient heat accumulation and thus the surface fire does not propagate upwards (fig. 11).

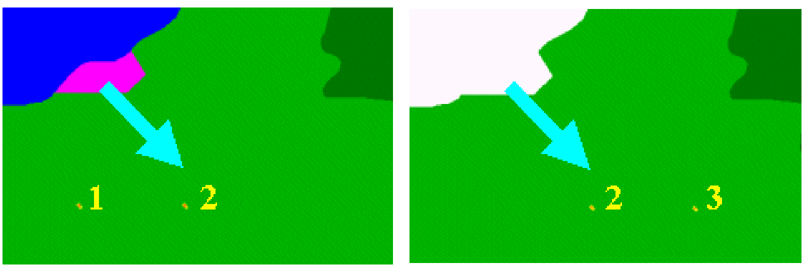

Figure 10. Surface (1) and crown fires (3) in windy conditions on the surface (left) and crown (right) layers.

As the wind slows (fig. 12), the fire shape reduces the eccentricity and the exchange of heat between the surface and the crowns intensifies till the ignition of the upper layer. In case the wind completely drops, the three fires reach asymptotically a cylindrical shape and continue to spread all in the same way.

Figure 11. The crown fire propagates to the surface (left), but not vice versa (right).

Figure 12. With less wind, the fires reduce their eccentricity and ignite the crowns (right).

5 THE SOFTWARE SYSTEM

The two-layer model described above is the core of a software package that has been developed to assist the coordinators of fire forces in case of emergency. The package performs a number of actions that can be grouped into three main sections:

- data retrieval and GIS functions
- fire simulation
- force coordination and communication.

We will summarize here the main activities performed in each section and show the interface that has been designed to be used by operators directly on the field.

5.1 *Data retrieval and GIS functions*

The main screen of the package is shown if fig. 13. The default map (normally a province, a catchments or whatever area is under the operator responsibility) is presented in its maximum extension (see box 2 in the figure); GIS data are loaded and standard tools are available to select the interesting area for the task. The user can zoom-in, zoom-out and pan till the visualized area responds to his/her requests and than save it by standard tools (box 3). Gauss-Boaga position of the map is always available together with the pixel scale, while the left panel (box 1) permanently displays the map legend .

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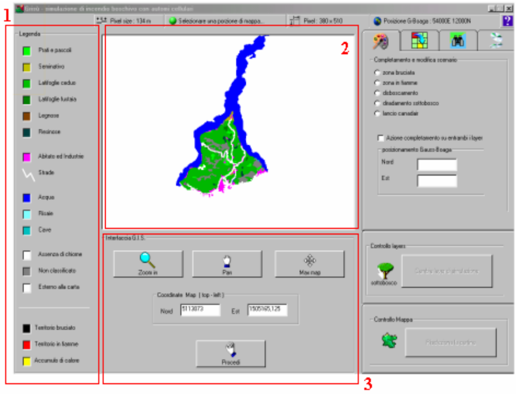

Figure 13. Main program interface

When the interesting region has been selected, information on altimetry and coverage is stored, and the map is locked. Clearly, the user may select a zoom larger than the DTM resolution, originally stored in the system, and this may cause a worsening of the simulation for some grid cells may be placed between two different elevation steps (see fig. 14, left). In such a case, the software informs the user about the critical zoom ratio selected, and suggests the use of a smoothing algorithm before proceeding with the simulation. The effect of this action is portrayed on the right side of fig. 14.

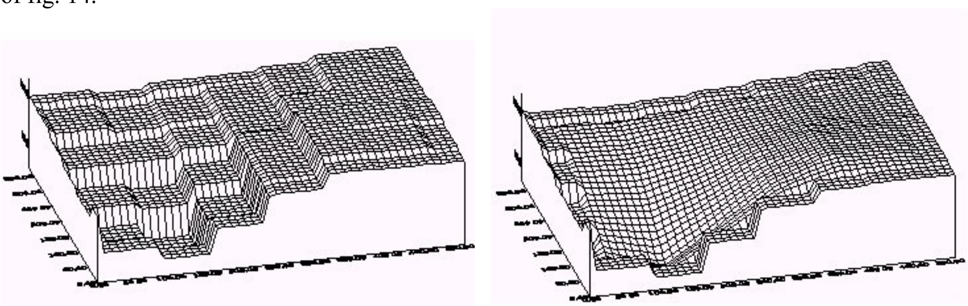

Figure 14. DTM before (left) and after smoothing.

Required meteorological variables, i.e. wind speed and direction, air moisture and temperature must be directly entered by the user in a suitable box appearing in the main screen, when the working map has been defined. The choice of using only one measurement for each meteorological variable (as opposite to the fields used by Lopes et al., 2002) is justified by two reasons: this software is designed to be used by local authorities in charge of limited areas, without much variability of meteorological conditions; several areas are being equipped with some automatic meteorological stations connected to the Internet through a modem, and thus, in the very near future, the system will be able to access the closest to the fire, using a mobile connection.

5.2 *Fire simulation*

This section lets the user insert, into the selected map, points of ignition, burned areas, fire-lines, fuel reduction to simulate any real scenario and test solutions to manage the operations. Gauss-Boaga positioning, pixel size information and three brush sizes help the user re-creating a scenario close to the real conditions (box 4 in fig. 15). User can interact jointly with both layers or take them separately.

This section also implements the two-layer model discussed above. The user can pause and save the simulation at any point, modify the scenario or set new meteorological parameters, and then continue or re-run the scenario to understand the impact of different actions.

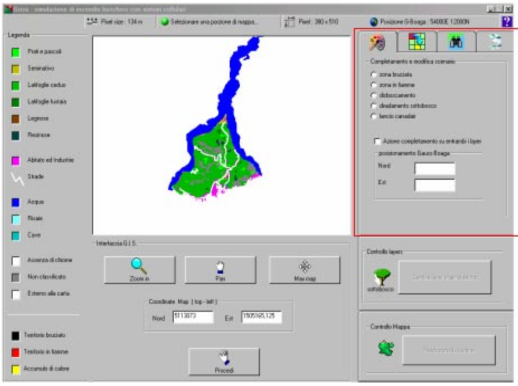

Figure 15. Fire scenario definition

Furthermore, he/she can check the situation of fire forces on the ground to control their positions and actions. GPS measures provided by such forces are directly read into the system, which maps their position and provides information on each of them by directly accessing a suitable database (see fig. 16).

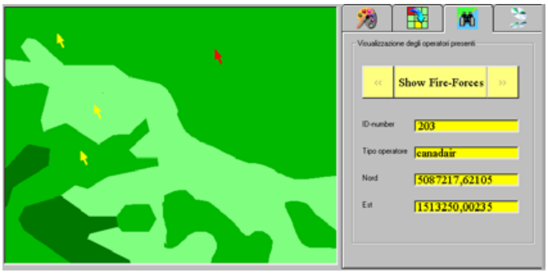

Figure 16. Operators positioning and database system.

5.3 *SMS and e-mail broadcasting services*

This final section provides tools to coordinate the work of operators and speed up all the message exchanging system. In particular, the software provides utilities for sending messages via GSM short message service (SMS) and by e-mail.

To reduce the number of operations and prevent errors (which may become a problem in emergency), the interface provides both a set of addresses/phone numbers grouped by responsibilities or zones and a set of standard messages (e.g., start of emergency, end of emergency, service notes) that can be sent by just clicking on them. User can obviously choose to modify the text of the messages in accordance with his/her necessity and maintain the personnel/facilities database by inserting, modifying, deleting items.

A windows on the screen is used to track the messages sent and displays the mobile phone numbers that have been reached or the e-mail addresses to which a message has already been sent.

6 CONCLUSIONS

A software system to support decisions on small scale fire fighting has been developed. Its core is constituted by a two-layer cellular automata model that can accurately portray the spatial dynamics of forest fires in complex landscapes. One of its limitations is the lack of a self-extinction mechanism: the fire is assumed to expand till it finds enough fuel. This assumption has been adopted both because information on this aspect is lacking and because, as a decision support, the system must produce a conservative forecast of fire development.

The software offers a friendly simulation/communication environment to the agencies in charge to rapidly retrieve relevant GIS data, check the effects of possible actions, monitor the deployment of fire forces on the ground and keep permanently in touch with them, even when working in a mobile center, simply equipped by a laptop PC and a GSM mobile phone.

The main characteristic of the cellular automata approach is its ability to easily incorporate several features present in the real systems. This flexibility has been enhanced in this software, since all the model and GIS parameters (for instance, the threshold values to be attributed to each vegetation type), as well as the databases, are stored separately on files, so that the software can be easily adapted to different terrains and situations.

ACKNOWLEDGEMENTS

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