GIS Procedure to Forecast and Manage Woodland Fires

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Abstract

Over the last few years, the phenomenon of woodland fires has become ever more widespread, this is also due to changes in climatic conditions; unfortunately, experience has shown that the consequences for the environment and human life are very serious if the extinguishing operations are not timely. Starting from a brief analysis of the most important available models to simulate fire evolution, the aim of this work was to propose a dynamic prototypal GIS to support the forecast of woodland fire spread and the management of the available resources for extinguishing operations. Currently GIS technology offers many tools for the implementation of analytical models that are useful to evaluate the temporal and spatial evolution of natural phenomena. Specific functionalities for network and lifeline management are also available that make it possible to create a decisional support system (DSS) to obtain the real-time optimization of resource allocation.

In this chapter we introduce a model-based approach developed in the GIS environment, in which a well-known fire spread model has been implemented and a specific analysis of the road network has been carried out to supply real-time information about the optimal route to reach fires. The proposed methodology has been applied to two different case studies: to the territory of Mount Etna (Province of Catania), and to the Province of Enna, both in Sicily. The result is a DSS GIS environment by which it is possible to evaluate and to display real-time maps about: (1) the velocity and the preferential direction of a simulated fire; (2) the best route to reach the front of the woodland fire.

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1 Introduction

Woodland fires are part of the 'historical' problems that threaten our natural environment. The high number of events that each year is registered around the world and the consequent great loss of wooded areas make it necessary to pay great attention to the measures that can be adopted to protect one of the most precious resources of a territory. In this sense, if it is opportune to adopt preventive and repressive measures, both useful to reduce the number of the events, on the other hand, when an event has begun, it is necessary to provide an efficient and quick coordination of air and land extinguishing means to limit devastating effects.

Therefore, to contain damage, it is absolutely indispensable to use the most advanced technology that allows the elaboration of realistic forecast scenarios of the evolution of the fire event, which will then be of great importance for planning and managing the emergency resources and services. In this sense, GIS technology, by which it is possible to elaborate spread models to simulate the front of fire movements, is really an answer for the above described problems. Moreover, as we propose in this chapter, it is possible to integrate these evaluations in a more articulated procedure that allows the identification, in different contexts, of the best path for extinguishing means to reach the fire.

The developed GIS, which represents a *Decision Support System* (DSS), can be profitably used not only during emergencies, but even during the phase of planning because, using the simulations of multiple predictable scenarios, it allows the identification of critical points of road networks for linking the fire front to the territorial resources necessary for the organization of the interventions.

2 Fire spread models

There are many available fire spread models: most of them are based on equations of energy conservation opportunely adapted by many tests and experiments to simulate the fuel behaviour of different materials. Some of the models, such as the one proposed by Rothermel (1972) or another proposed by Albini (1976), are not very recent but they are still frequently used today. There are also more recent models such as FARSITE (Fire Area Simulator, Finney, 1998), which is a deterministic and mechanistic model of forest fire growth and spread based on existing fire behaviour models of surface fire spread (Albini 1976, Rothermel 1972), crown fire spread (Rothermel 1991, Van Wagner 1977, 1993), spotting (Albini 1979), point source fire acceleration (Forestry Canada Fire Danger Group 1992), and fuel moisture (Nelson 2000). Another important model is Prometheus (2006), which is a deterministic fire growth simulation model, coming from a national interagency project endorsed by the Canadian Interagency Forest Fire Centre (CIFFC) and its members. It uses spatial fire behaviour input data on topography (slope, aspect and elevation) and FBP fuel types, along with weather stream and FBP fuel type lookup table files. Another important model is Phoenix, which is one component of a bushfire risk management model, developed by Bushfire CRC, for southern Australia.

In this chapter the focus is not connected to the qualities or the differences between models, but the purpose is to verify the possibility of implementing models into the GIS environment, in order to relate the simulating results to the other typical spatial functionalities, such as network analysis or management. For this reason, the model we chose to realize this GIS application is the 'traditional' one proposed by Rothermel in 1972, a milestone in this sector: this model, in fact, is still today one of the most used and it is the basis of many others. Running the simulation model into GIS environment, we wanted to propose a wider integrated woodland fire emergency management application in which also resources for extinguishing are taken into account, as well as providing the best routes on the available road network.

In particular, the model of Rothermel can represent the 'behaviour' of an advancing fire that spreads in homogeneous and continuous fuel, carrying out the speed of the fire-head (that is the quickest part) so that it is possible to evaluate the potential path of the fire itself. In a more detailed way, Rothermel's equation has been developed into the hypothesis of superficial, uniform, continuous layers adjacent to soil, made of live and dead combustible material, of 2 m thickness, in stationary conditions and distant from heat source that started the fire. The model describes the way in which a fire moves forward in combustible material as a series of ignitions that progress like a 'contagion', and it expresses the speed that brings the fuel bands adjacent to the fire front to the ignition temperature. These characteristics are particularly useful in implementing the model in GIS environment. Without any other theoretical details, for which we suggest specialist studies, we draw your attention to Rothemel's equation:

$$R = \frac{I_r \xi \left(1 + \Phi_W + \Phi_S\right)}{\rho_b \varepsilon Q_{ig}} \qquad (1)$$

where R is the fire front propagation speed [m/min], I_r is the reaction intensity [Kcal/m^2 min], ξ is the propagating flux ratio, Φ_w is the wind coefficient, Φ_s is the slope coefficient, ρb is the ovendry bulk density [Kg/m^3], ε is the effective heating number, and Q_{ig} is the heat of pre-ignition [Kcal/Kg]. In the formula (1), the numerator represents the quantity of heat that combustible material has received; the denominator, instead, is the heat quantity necessary to bring it to ignition temperature. Because a detailed knowledge of these factors is very difficult, Rothermel reduced the different vegetal typologies to different combustible material 'models', useful for immediate application by the formula.

3 Implementation of the model and simulation of a fire event by GIS

This study was applied to two sample areas: Etna Park (Province of Catania), on the east side of the volcano, where a thick road network that drives into the wooded areas is present, and in another area in the Province of Enna, where many fires have burnt large tracts of woodlands over the last few years. The latter is very good because we have much information about woodland characteristics and data about past fires useful for comparison with the results of simulations. As concerns the Etna Park sample area, its territorial conformation is perfect to the GIS implementation we propose in this chapter, both for the model application and for network analysis. The model of Rothermel was implemented in GIS environment by a series of GRID themes, each one corresponding to one of the variables in the equation. The informative contents of some themes (Ig, ξ, ρ_b, ε, Q_{ig}) was mainly obtained not only from scientific literature data (combustible models) that referred to the characteristics of dominant vegetation species in studied wooded areas, but also from information (such as tree density, or the average concentration of combustible materials on the soil, etc…) deduced from documentation and thematic maps that are the property of the Province of Catania Administration and Etna Park Organization, or the property of the Province of Enna. The GRID theme linked to slope coefficient (Φ_s) was calculated by a *Digital Terrain Model* (DTM) of the studied area that resulted in a slope map. As concerns the wind coefficient (Φ_w), an index that represents the exposition and the scalar speed of wind, a uniform value on all cells was assumed.

For each of the realized GRID themes we adopted just one cell dimension, 10 × 10 m, because of the necessity of a continuous comparison with the vector themes of the road network. This dimensioning, that in relation to the general scale of the work (1:25000) could appear of excessive detailing, is absolutely necessary both for the physical elements that are involved in the modelling procedure, and to give reliability to the verification of the approaching path of extinguishing means, as we show in the next part of the chapter. Using the application of Rothermel's equation to the above described themes, we obtained a new GRID map where the value of each cell represents the potential spreading speed of the fire front expressed in meters/minutes (Fig.1).

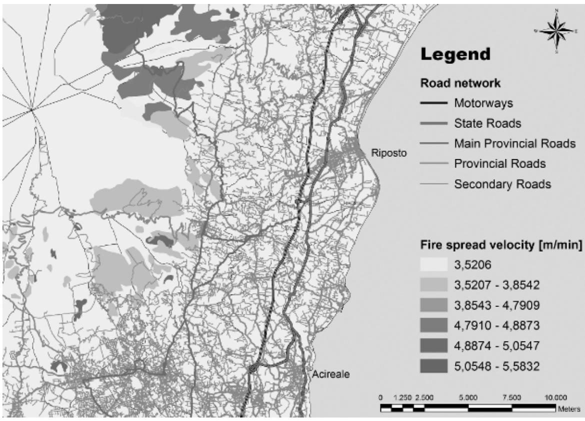

Fig. 1. Speed of fire front spreading evaluated by the Rothermel model (Etna)

At this point, because the first objective was to determine the spreading times and the distances covered by the fire front, a process of data elaboration was activated, finalized to use some proper GIS functions opportunely adapted to specific themes that we were working on.

A first elaboration was carried out to produce a new GRID theme in which each cell is associated to the inverse of the calculated spreading fire velocity. On this last GRID, after we made the hypothesis of a punctual origin of a fire, a spatial analysis using the function *Distance*→ *CostWeighted* was realized; in this way, we obtained a new GRID theme, in which the value of each cell represents the time (in minutes) necessary for the same cell to be reached by the fire from the supposed origin. The *CostWeighted* function was adapted to the modelling of the phenomenon, using as 'impedance' a referring GRID theme (to be more precise, the inverse of the fire spread speed, calculated thanks to Rothermel's model) and multiplying the values of each cell for the relative distances from the punctual hypothesized origin (in meters). In this way we obtained, cell by cell, a map of the necessary times for the fire ignition, based on the calculated fire spread speed and on the hypothesized origin (Figs. 2 and 3).

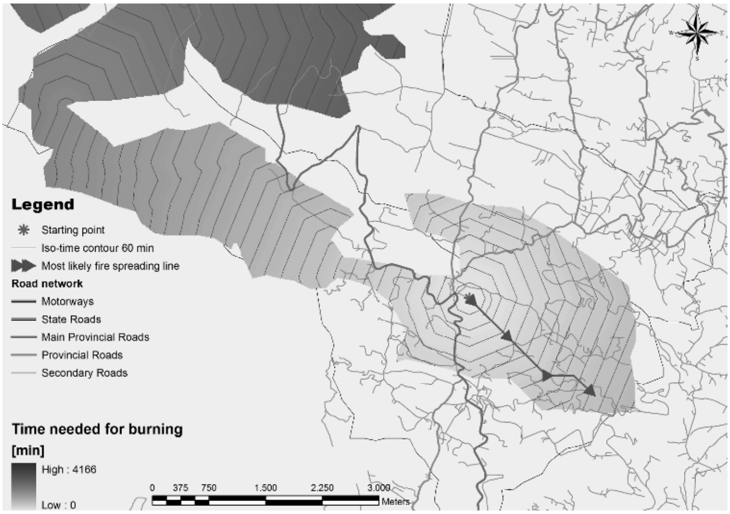

Fig. 2. Map of time needed for ignition and most likely line-path of the fire spread (Mount Etna, wind coming from North-West to South-East)

Thanks to this last elaboration, it was possible to elaborate another spatial analysis using the Distance→ ShortestPath function to identify the most probable approaching path of the fire. The ShortestPath function works on the GRID obtained by the Costweighted function, elaborating it again in function of a punctual destination that has to be assumed. The line that joins this destination point with the hypothesized other point for the origin of the fire defines the main wind direction that, in case of considerable air speed, is certainly the same direction of the most likely spreading of the fire front. Therefore, the ShortestPath function carries out, on the basis of the last evaluation about potential fire speed and the main wind direction, a path, made by 'minimum cost' cells: these are the cells where the fire spread is most likely, because the tendency to burn is higher. The ShortestPath function, of course, allows the identification of only a 'line of contiguous cells', which is not directly connected with the real width of the fire front; to represent in a more realistic way the phenomenon (in the hypothesis of constant speed and wind direction) it could be possible to use an average ‘opening angle’ on the origin point, using values inversely proportional to the wind velocity. At the end of the described elaborations it was possible to extrapolate iso-time contours on the GRID theme obtained by the CostWeighted function, which represent the place of the points (or, better, of the cells) that could be reached by the fire at the same time (Figs. 2 and 3). Verifying the intersections between the iso-time contours and the main spreading path of the fire front evaluated by the ShortestPath function, it was possible to make available a methodology to understand the advancing of the simulated fire in time and space.

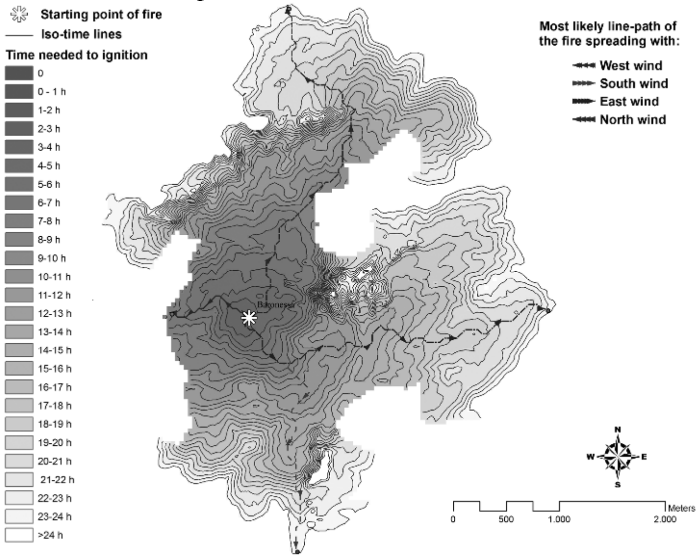

Fig. 3. Map of time needed for ignition and most likely line-path of the fire spread (Baronessa, in the Province of Enna, wind directions North, East, West, South)

4 Road network analysis to identify and update in real time the best approaching route for extinguishing means

The time-space simulation of woodland fires carried out by the proposed methodology can be profitably used to optimize the management of the emergency, based on the available territorial and infrastructural resources. Using a GIS network analyzer module, it is possible to identify the best operation center, (for example, a fire-brigade) that is able to make its land means reach the fire front first, and to choose the best approaching route. During the time needed to reach the ‘destination’ indentified when the alert started, it is possible that the fire front has gone beyond the destination itself or has destroyed some sections of the assigned path because of the variability of the phenomenon in relation to meteorological conditions. In this sense, a second quick verification of first selected path is needed and eventually its new definition, updating the destination and, if necessary, excluding road sections not useful for interventions.

The network analyzer, considering the characteristics of roads selected for the approaching path and the real traffic conditions can be also used to obtain real-time evaluations of travel time and to verify the position of means in relation to the contextual evolution of the fire front spread. To obtain these results, the RTK transmission of the position surveyed by GPS receivers installed on extinguishing means would allow the main operation center to evaluate, minute by minute, the movements and possible delays (for example due to traffic) of its squads and to elaborate again the proposed methodology to update the approaching route.

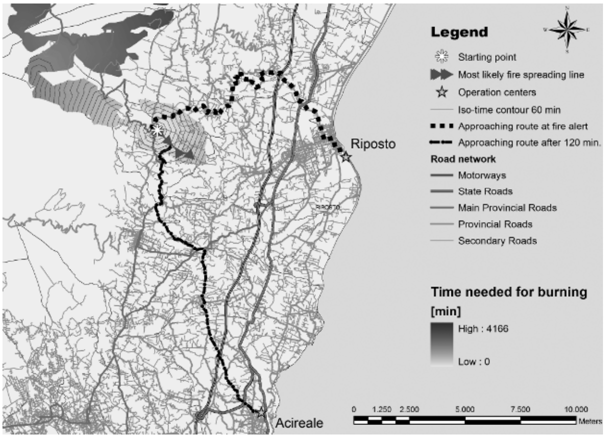

Fig. 4. Identification of the optimal approaching route in function of the most likely fire front position

For example, in Fig. 4 we show two different approaching routes: the one represented with dashed line has been evaluated by the network analyzer considering the position of the fire at the alert time; the one given with continues line refers to the most likely position of fire front after 120 min. It is useful to notice that the second solution (that also takes into account the travel time) consists not only of the evaluation of a new path, but also of the possibility of selecting a new starting point. This is very important to manage the emergency, because it is possible to identify the best operation center to be activated for the operations. The flow hart of Fig. 5 summarizes the different phases of the proposed procedure.

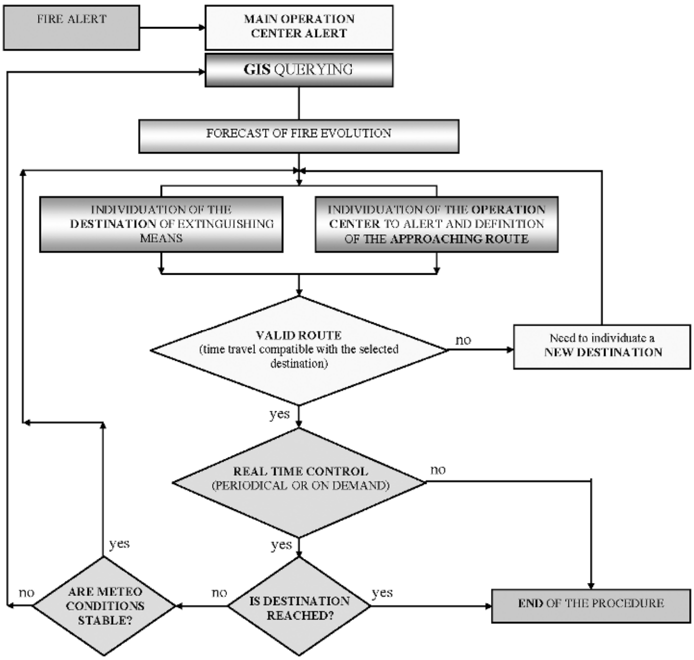

Fig. 5. Flow chart of the proposed procedure

5 Conclusions

The proposed procedure is based on GIS functions that can build a decisional support system useful both to manage fire emergencies and to provide precautionary plans, related to critical points that the system is able to highlight by the simulation of scenario events. After a short analysis of available fire simulation models, we chose Rothermel's model, which is one of the most used. Different tests were carried out on the mountainous area of Etna and in the territory of the Province of Enna, implementing the chosen model on wooded areas. The procedure is articulated in two different, independent but interconnected phases: a spatial analysis that allows the simulation of the fire spread by the implementation of Rothermel's model on specific GRID themes; a network analysis extended to the road network system, that defines and, eventually, updates the best origins and routes for extinguishing means, also evaluating travel time.

The emergency management would be helped by the use of 'real-time' GIS, using information that could be transferred to the main operation center by GPS receivers installed on the extinguishing means moving to the fire front, and by a special meteorological parameter monitoring system.

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