An Integrated System for the Forest Fire Dynamics Hazard Assessment Over a Wide Area

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Abstract: An integrated approach is presented for the assessment of forest fire hazard over a wide geographical area on the basis of real-time information, meteorological forecasts, and territorial data stored in a geographical information system. The paper describes the architecture of a comprehensive system that can be designed in order to manage the overall forest fire risk. Specifically, vegetation modelling, in connection with local meteorological conditions and topography, allows obtaining forecast of the dynamics of moisture contents of the different kinds of dead and live fuels over a wide geographical area. Besides, a semi-physical fire propagation model gives a quantitative evolution of the hazardousness over the whole considered region. Such hazardousness is related to the spread behaviour of a potential fire after an accidental or deliberate ignition. A dynamic hazard assessment is carried out, as hazard distribution in time and space and is determined over a certain time horizon (24/72 hours). The purpose of dynamic hazard assessment is that of getting reliable information useful to take a number and a variety of pre-operational actions that can reduce the impact of potentially lighted fire over the considered territory, within the considered time horizon. An application of the system is described over the whole Italian territory relevant to the Joint Operation Center of the Italian Civil Protection, in order to demonstrate the effectiveness of the proposed approach.

Keywords: forest fire, dynamic modelling

1. INTRODUCTION AND OBJECTIVES OF THE PAPER

The forest fires phenomenon is strictly related with land use and vegetational characteristics of the area where the ignitions have been effected. As a matter of fact, in Mediterranean basin, forest fires occurrence is almost in all the cases attributable to man (either as a voluntary action or as an involuntary consequence of some activity), whereas in other geographical areas a great number of fires are caused by lightning activity. However, in all the cases, the propagation is heavily influenced by the characteristics (topography, vegetation, etc.) of the interested territory, as well as by the meteorological conditions and the conditions of the fuel (mainly as regard its moisture content). From the above discussion, it is clear that, in general, it is improper to think of forecasting ignition, whereas, it is sensible to assess and forecast the danger that a (somehow) active fire may find favourable conditions for its propagation.
In this connection, the purpose of the paper is that of presenting an integrated approach that has been developed in order to assess the forest fire hazard over a wide geographical region, on the basis of all available information.

The rest of the paper is organized as follow. In the next section the architecture of the developed system for dynamic forest risk assessment is presented. In the third and in the forth sections, the fuel moisture and the initial spread model actually implemented in the system, are introduced. In the fifth section, the software implementation of the system is described and some results concerning the application of the system to the Italian territory are briefly presented. Finally, in the last section some conclusions are drawn and some possible directions for forthcoming research activity are indicated.

2. THE STRUCTURE OF THE HAZARD ASSESSMENT MODULE

The paper describes a first implementation of a "dynamic hazard assessment procedure", whose structure (see Fig.1) may be decomposed into two sub-models, namely the *fuel moisture model* and the *initial fire spread model*. The function of the fuel moisture model is to represent the dynamic behaviour of the distribution throughout the territory of the variable expressing the water content of the fuel that is mostly interested by the ignition process. The second model is used to quantitatively describe the behaviour of a (possibly) lighted fire, disregarding any possible extinguishing action. Such a model is not used to obtain a forecast of the propagation process of a given fire, but only to evaluate the risk of potential spread after a possible ignition.

The information that can be used by the two sub-models represented in Fig. 2 is both static and dynamic. The first is related to topographic and territorial data (topography, land use, road networks, etc.) which can be obtained from a Geographical Information System (GIS), and to the vegetation cover of the areas considered. Note that vegetation cover (biomass kind and density) may be included within static information; in fact, seasonal biomass dynamics is much slower than the dynamics of the two models represented in Fig. 2, so that one can reasonably think of considering the average vegetation load for each season of interest.

On the other hand, dynamic information may be diverse in nature. First of all, there may be a network of ground sensors (rain gauges, anemometers, solar radiation sensors, etc.) capable of providing real-time measurements of variables whose importance is apparent for the evaluation of forest fire hazard. Other sensors may be used to acquire information related to fuel moisture. For instance, the use of remote sensors (installed on aircraft or satellites) may provide real-time information about the state of vegetation. Such information may refer, for example, to the tissue moisture content or to some measure of water deficit index (Burgan et al., 1996). In addition, remote ground sensors can provide real-time information about the meteorological conditions over the territory, or data concerning the drought level of vegetation. Finally, valuable dynamic information is also represented by the outputs of a meteorological model, assuming that the forecasts over a suitably long horizon [e.g., 48-72 hours] can be considered sufficiently reliable. Note that, in principle, several different meteorological models can yield a notion about the uncertainty of the meteorological forecasts. As such forecasts are provided by the model over a time horizon, even the forest fire hazard assessment that is obtained by the overall module in Fig. 2 refers to such a horizon, and thus may be represented as a set of functions of time and space, one for each physical variable that is assumed to be significant to assess forest fire hazard.

For the sake of simplicity, the above functions may be chosen to be discrete both in time and space. A suitable choice for the time discretization interval and the space discretization grid is that of taking the same time-space discretization that characterizes the outcomes of the meteorological model. In particular, the variables that are determined to evaluate and represent the forest fire hazard on each cell of the space grid (and for each time interval) are the rate of spread and the linear intensity that a fire could assume (in case of ignition). Note that the former's potential rate of spread is obtained through the application of a model that is not used to evaluate the dynamics of a given fire, but to evaluate the physical characteristics that a fire could take on, in each cell, on the basis of the variables that locally condition the possibility of a successful ignition and fire propagation.

The system receives the daily outputs of a meteorological Limited Area Model (LAM), namely Lokal Modell (Doms and Schättler, 1999), consisting of a set of data discretized in time steps of three hours over a time horizon of 72 hours, and defined over a regular grid composed of 57.200 cells having a side corresponding to 0,05 degrees. The available meteorological (forecast) variables are the cumulated rainfall [m] in each three-hour time interval, air temperature [K], dew point temperature [K], wind speed [m s-1], and wind direction [rad]. In addition, a Digital Elevation Model (DEM), defined over a regular grid of 5.000 m side, has been utilized to represent the topography of the target area. This model is used to define the average value of the aspect angle [deg], the slope [%], and the elevation [m] of each grid cell.

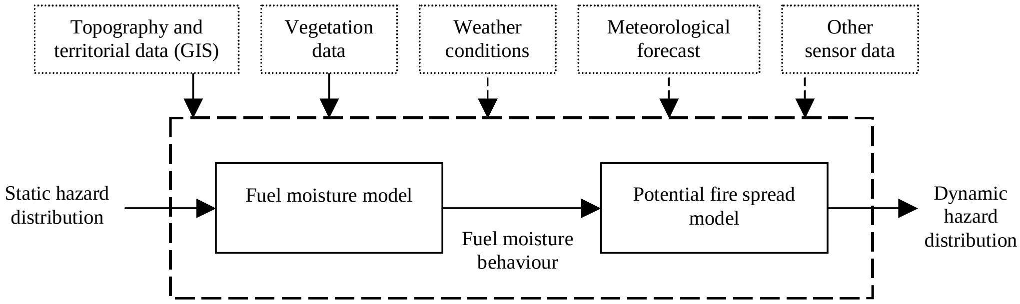

Figure 1. A schematic representation of the structure of the dynamic forest fire hazard assessment module

The vegetational characteristics have been introduced in the system by means of a vectorial map of the whole area (e.g., the CORINE Land Cover map). In the proposed procedure, a regular grid of 0,0125 degrees of side length is introduced, in order to define the distribution of fuels in space and their characterization in terms of physical-chemical properties. The available fuels can be described by specifying their morphological parameters and the behaviour of their physiological variables. It is assumed that the values of such morphological parameters cyclically vary over the year. In this connection, a *quasi*-stationary model has been adopted, and the average seasonal value has been used for any parameter. For each different reported species, the seasonal fuel loads [kg m^{-2}], has been obtained from the literature (Anderson, 1982; Nunez-Regueira *et al*., 1999) and then organized in a GIS database. Moreover, the physiological characteristics of the fuels, that is the average seasonal tissue moisture content [%] of live fuel for each species, have been also introduced in the GIS database, as well as the average seasonal Higher Heating Value (HHV) [kJ kg^{-1}], both for dead and live fuels.

In the present implementation, the only dynamic information provided to the models, is represented by meteorological forecasts, and other kinds of dynamic information are not used. Nevertheless, as it will be discussed in the next sections, even in its present version, the module can be considered as on operative tool, and the results of its applications are quite encouraging.

3. THE FUEL MOISTURE MODEL

In the present implementation of the dynamic fire hazard assessment system, only the dynamics of the dead fine fuel is modelled. Instead, the live fuel moisture is considered practically time-invariant, and is provided by values corresponding to the specific vegetation cover and to the considered season (Brown *et al.,* 1989).

The dynamics of the dead fine fuel moisture is represented by using for each cell k over the considered region a specific model, which does not interact with the models of the other cells, as no fire propagation is represented. Then, let $u_k^o(t)$ represent the dead fine fuel moisture at cell k at time instant t. It is assumed that the evolution of the above quantity is governed by the differential equation

$$\frac{du_k^o(t)}{dt} = K_1 \,\mathrm{step}(t) - K_2 \, u_k^o(t) \qquad (1)$$

where step(t) is the unit step function[1]. In fact, the solution of (1) has an asymptotic behaviour determined only by the ratio (K_1/K_2), namely

$$u_k^o(t) = \frac{K_2 \, u_k^o(0) - K_1}{K_2} e^{-K_2 t} \,\mathrm{step}(t) + \frac{K_1}{K_2} \mathrm{step}(t) \qquad (2)$$

Of course, the asymptotic value (K_1/K_2) is independent of the initial state $u_k(0)$, and the transient behaviour decays (increases) if $u_k(0) > (K_1/K_2)$ $(u_k(0) < (K_1/K_2)$. Observe that the "time constant" characterizing the speed at which the transient term in the r.h.s. of (2) vanishes is given by $1/K_2$.

Note that the solution (2) of eq. (1) is correct only in the assumption of time-invariance of coefficients K_1 and K_2, which, however, as will be discussed below, must be considered time-varying, since their values depend on a set of meteorological variables. Thus, the use of solution (2) is correct only whenever the dynamics of model (1) (which is characterized by the time constant $(1/K_2)$) is considerably slower than meteorological dynamics (determining the

[1] Function step[x] is defined as equal to 1 if $x \geq 0$ and equal to 0 otherwise.

variation of K_1 and K_2). However, discretization of (2) is in any case allowed, even when K_1 and K_2 are significantly time-varying. For this reason, hereafter the dependence of such coefficients on time (and on cell k) will be explicitly recalled by the notation.

It is assumed that coefficients $K_{1,k}(t)$ and $K_{2,k}(t)$ are functions of the meteorological variables $p_k(t)$, $w_k(t)$, $\rho_k(t)$, $\tau_k(t)$, that is the cumulated rain $p_k(t)$ [m], the wind intensity $w_k(t)$ [m s^{-1}, rad], the relative humidity $\rho_k(t)$ [%], and the air temperature τ_k [K]. In the proposed model, instead of trying to model such a dependence through thermodynamic considerations, a semi-physical structure is proposed by assuming that the asymptotic value $(K_{1,k}(t)/K_{2,k}(t))$ can be expressed as a function of the meteorological variables as follows

$$\frac{K_{1,k}(t)}{K_{2,k}(t)} = e^{\frac{\rho_k(t)+\alpha_1}{\alpha_2+\alpha_3\tau_k(t)}} \qquad \text{if } p_k(t) \le p^* \qquad (3)$$

$$\frac{K_{1,k}(t)}{K_{2,k}(t)} = \beta_1 \qquad \text{if } p_k(t) > p^* \qquad (4)$$

where α_i (i=1,..,3), β_1 are constants having suitable dimensions and p^* [m] is a threshold value for the cumulated rain. Note that (3) applies in the absence of significant rainfall (in the last time interval), whereas (4) holds true whenever such a rainfall cannot be neglected. Of course, the constant values must be selected so that

$$\beta_1 > e^{\frac{\rho_k(t)+\alpha_1}{\alpha_2+\alpha_3\tau_k(t)}} \qquad (5)$$

for any possible value of $\rho_k(t)$, and $\tau_k(t)$. Note that the dependence of the r.h.s. of (3) on $\rho_k(t)$ can be justified by observing that the higher the value of $\rho_k(t)$ is the higher the asymptotic value of $u_k^o(t)$ will be[2]. Besides, the fact that the r.h.s. of (4) is independent of $p_k(t)$ can be justified by the assumption that the asymptotic values of the fuel moisture are independent of the rainfall intensity (whenever such an intensity exceeds a certain threshold). Finally, the fuel moisture is uncorrelated with temperature and humidity in case of rain, since rain raises the fuel moisture condition to the fiber saturation point, which is greater than 35% (Cheney, 1981).

As regards the dependency of $K_{2,k}(t)$ from meteorological variables, recalling that $1/K_{2,k}(t)$ is the time constant which (in time-invariant meteorological conditions) characterizes the transient behaviour represented in (2), makes so that, in absence of a significant rainfall, a high value of temperature and wind intensity favours drying but hampers moistening. Instead, in presence of significant rainfall, provides a linear dependence of the moistening speed on the rainfall intensity.

At this point, after model (1) has been discussed, also as regard the dependence of the coefficients appearing in (1) on the meteorological variables, it is worth explicitly providing the discretized version of the model that is actually implemented in the developed system, namely

$$u_k^0(t+1) = u_k^0(t)\left[1 - T\, K_{2,k}(t)\right] + T\, K_{1,k}(t) \qquad (6)$$

where T is the length of the discretization interval (3 hours), and the time variable t is now an integer number.

The behaviour of the fuel moisture model is deeply affected by the value of the parameters; an accurate calibration of such parameters could take place by means of suitable parameter fitting techniques and on the basis of a wide set of real data. Such a calibration is beyond the scope of this paper, also because of the difficulty of obtaining reliable and significantly distributed data regarding fuel moisture. An estimate of such parameters derive from empirical evidence over a wide set of test cases (relevant to detected fires) that will be described in the following and that refer to the overall performance analysis of the integrated system consisting of the cascade of the fuel moisture model and the potential spread model.

4. THE POTENTIAL SPREAD MODEL

The dynamic information that this model uses is that related to meteorological forecast variables, and that provided by the fuel moisture model. At the same time, the propagation model makes use of information related to topography and vegetation (kind and density per m2), again referred to the considered cells. The information concerning density and kind of dead and live fuel for each cell is considered as static, since only seasonal variations are considered simply by taking into account different values of the relevant parameters for the various seasons.

The development of the potential fire spread model follows the same basic lines first proposed by Drouet (1974) for the definition of a forest fire propagation model, but introducing some important novelties as regards the procedures to evaluate the forest fire hazard.

[2] Note that such an asymptotic values is actually only “potential”, as it is achieved only when meteorological conditions are time-invariant.

The first information on which the potential spread model is built is represented by the *nominal rate of spread* $v_{0,k}$, which is a quantity referring to standard conditions as regards the temperature and the average live fuel moisture, in absence of wind, within a perfectly flat terrain, and with perfectly dry dead fuel. Obviously, $v_{0,k}$ depends on cell index *k*, as it depends on the kind of fuel (i.e. particle size, bulk density, moisture, and chemical composition of the fuel) and on the vegetation density (biomass per square meter) of live and dead fuel. Besides, such a value has to be specified in connection to the various seasonal conditions, as they determine the average moisture of live fuel. Clearly, the determination of $v_{0,k}$ needs a great amount of experimental tests and a deep knowledge on the vegetation covering over the territory. On this basis, the *potential rate of spread*, which takes into account the influence of the meteorological variables, can be defined and determined as follows

$$v_k(t) = v_{0,k}\ Z_k(t)\frac{W_k(t)}{N_k(t)} S_k\ V_k(t) \qquad (7)$$

where

$Z_k(t)$ is a (multiplicative) correction [dimensionless] due to air temperature, at time t and in cell k, with respect to the std. temperature (0°C) assumed as the reference one;

$W_k(t)$ is a (multiplicative) correction [dimensionless] due to wind speed on flat terrain, at time t and in cell k;

$N_k(t)$ is a normalization term [dimensionless] which takes into account the influence of topography on coefficient $W_k(t)$;

S_k is a (multiplicative) correction [dimensionless] due to the slope of the cell k;

$V_k(t)$ is a (multiplicative) correction [dimensionless] due to the dead fine fuel moisture, at time t and in cell k.

The correction terms introduced above are defined as parametric functions of the considered information (slope, aspect, meteo variables), based on empirical evidence.

Having thus clarified the way to compute the potential rate of spread $v_k(t)$, which provides a quantification of the swiftness characterizing the (potential) spread of a fire, it is necessary to also quantify the intensity of the phenomenon, which is the ultimate measure of the hazard. To this end, Byram's equation (1959) can be used to determine the (potential) fire linear intensity $I_k(t)$ [kW m^{-1}], namely

$$I_k(t) = v_k(t)\sum_{i=0}^{1} LHV_k^i\ d_k^i \qquad (8)$$

where

d_k^0, (d_k^1) [kg m^{-2}] is the density of dead fuel (live fuel), for the considered season in cell k;

$LHV_k^0(t)$, (LHV_k^1) is the Lower Heating Value [kJ kg^{-1}] of the dead fine fuel (live fuel) in cell k at time t, given by:

$$LHV_k^0(t) = HHV_k^0\left[1 - u_k^0(t)\right] - Q\ u_k^0(t) \qquad (9)$$

$$LHV_k^1 = HHV_k^1\left[1 - u_k^1\right] - Q\ u_k^1 \qquad (10)$$

where

HHV_k^0, (HHV_k^1) is the Higher Heating Value [kJ kg-1] of the dead fine fuel (live fuel) based on the prevailing species composition in cell k.

5. SOFTWARE IMPLEMENTATION

Since August 2003 a prototype of the system provides to Italian Civil Protection a daily fire hazard assessment for a 72 hours time interval. The system has been implemented in a MS Visual C^{++} procedure integrate, as it shown in Fig. 2, in a pre-existent GUI integrated in a dedicated network and used by the Civil Protection for the data processing and the visualization of information relevant to the other natural hazards.

The system receives daily at 6:00 AM from a remote station 120 ASCII files (66 MB) elaborated by the LAM run of 00:00 AM and relevant to the national meteorological forecast for the next 72 hours. As it concerns the static information, the Italian vegetational cover and the topographic characteristics are stored in 1 file of 1025 KB. The computation environment is a Windows XP operational system equipped with AMD Athlon XP 2000 2 GHz CPU, 256 MB RAM. The time needed for the creation of the whole set of files is about 50 seconds. The output files are 7 (10 MB), defined for each time 3-hour interval belonging to the 72 hours time horizon, and for each cell of 0,05° side covering the whole target area, i.e. the Italian territory, measuring 302.000 km^2 Each file defines the following greatness: the air temperature contribution to the rate of spread [dimensionless], the wind speed contribution to the rate of spread [dimensionless], the dead fine fuel moisture [%], the maximum rate of spread [m h^{-1}], the rate of spread [m h^{-1}], the linear intensity for each cell [kW/m], and the linear intensity aggregates for each Italian regional district [kW/m]. Each output file is in

ASCII format and is composed by 26 column and 13.265 rows. The first and second column represents the coordinates of the cell, whereas the other 24 columns represent the values of each variable for each time interval.

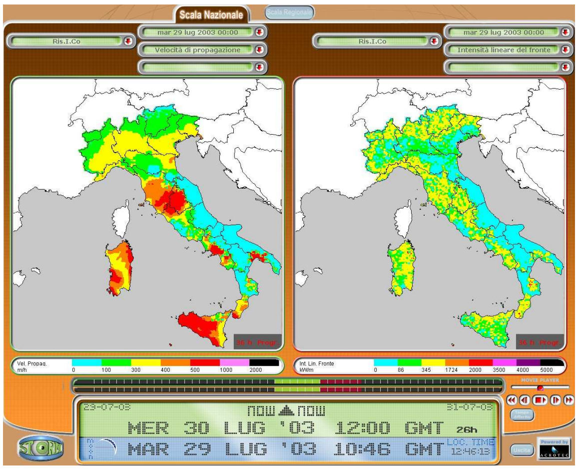

Figure 2. The Civil Protection GUI outputs relevant to forest fires dynamic hazard assessment over the Italian territory. The (animated) image at left side of Fig. 2 is the potential rate of spread [m h^{-1}] for the next 24 hours, whereas at right the linear intensity [kW m^{-1}] relevant to the same time interval is reported.

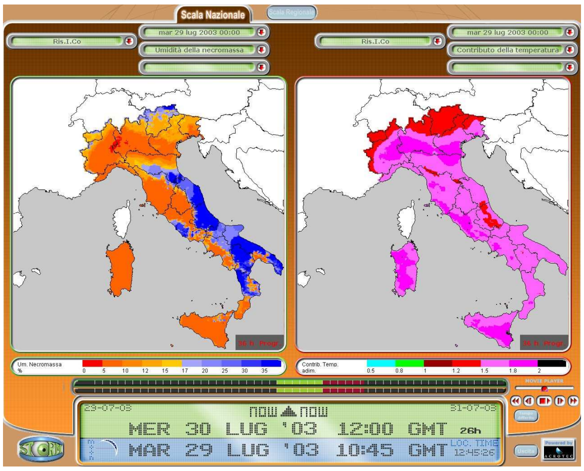

Figure 3. On the left the dead fine fuel moisture [%] relevant to a 24 hour forecast; on the right the air temperature contribution to the rate of spread [dimensionless] relevant to the same time interval.

6. CONCLUSIONS AND FURTHER RESEARCH DIRECTIONS

Several practical as well as conceptual problems remain to be investigated to assess the validity and the practical relevance of the proposed approach. Experimental evaluation with reference to a real case study is presently carried out within the Italian Civil Protection Department, which is charged to manage and dispatch the fleet of amphibious water bomber (CL 415 Canadair) and heavy helitanker (S64F Air Crane) on national high-risk areas or on signalled active fires.

7. ACKNOWLEDGEMENT

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