Nation-wide forest fire risk assessment. Performance analysis and validation of two different dynamic fire weather systems in Italy

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Abstract

Since 2003 the Italian national Civil Protection make use of a specific systemfor the dynamic forest fire risk assessment named RISICO (RISchio Incendi & COordinamento). The rationale of the RISICO system is to provide decision makers with reliable estimation of the state of the fuel (moisture conditions) and the physical characteristics (ROS and fire line intensity) that a fire could assume after a successful ignition.

The structure of the system is basically made of a fuel moisture model and a fire spread model, provides decision makers with nation-wide risk forecasts relevant to a time horizon of 72 hours, discretized in time interval of 3 hours, over a 5 km grid.

The dynamic information that feeds the system is provided by the deterministic run of a meteorological non-hydrostatic Limited Area Model (LAM). The used meteorological variables are the 3-hour cumulated rainfall, the air temperature, the relative humidity, and the wind speed and direction.

In the paper, after a short description of the system, its calibration along with the validation phase is presented and discussed in detail. The information obtained from the analysis of a wide set of data relevant to the wildfires occurred in Italy from 01/01/2004 to 31/12/2005 has been compared with the information generated by the system.

The performance indexes selected in order to measure the system effectiveness are relevant to the capability of identifying the correct risk classes (in terms of fire line intensity) with reference to the area and duration of the wildfire, and to the capacity in discriminating a relative limited number of clusters of cells characterized by the higher danger classes. This second target represents a major issue for Civil Protection, since the number of resources that have to be assigned on the territory in the pre-operational phase is relatively scarce with respect to the areas denoted by non-negligible danger levels.

A comparison among the performances obtained by RISICO versus the performances obtained by the Canadian Fire Weather Index (FWI) concludes the paper.

Introduction

Wildland fires heavily affect the Italian peninsula and its islands. In fact, rainfalls concentrated in few days of wintertime, drought-ridden summers and

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persistently strong winds make the vegetation particularly vulnerable to ignitions and propagation. Moreover, the dramatic changes in socio-economic conditions over the last few decades have increased the area of forest in contact with settlements and human activities, such as pasturage, agriculture, industry, thus making the odds of fire occurrence exceptionally high. As a matter of fact, in Mediterranean countries at least, the ignition of a fire is nearly always attributable to man (either as a voluntary action or as an involuntary consequence of some activity) and, therefore, not recognizable as a natural event. By contrast, the fire propagation is heavily influenced by territorial characteristics (topography, vegetation, etc.), as well as by meteorological conditions. On the basis of these considerations, it is clear that it is improper to attempt the forecasting of ignition itself, whereas it is sensible to assess and forecast the danger that a (somehow) ignited fire may find conditions favoring its propagation.

The purpose of this paper is that of presenting a wildland fire danger rating system, named RISICO (RISchio Incendi e COordinamento), developed by the authors in order to assess the risk over the Italian territory, over a 72 hours time horizon, on the basis of all available information, including meteorological forecasts provided by a Limited Area Model (LAM). This system is presently used in Italy by the Dipartimento della Protezione Civile (DPC) as regards the dynamic assessment of wildland fire risk over the whole national territory. The main use of the information provided by such a system is that of supporting decision makers, at national level, in all decisions concerning the issuing of alert messages to regional authorities. The structure of RISICO system is conceptually similar to that of CFFDRS (Canadian Forest Fire Danger Rating System; Stocks et al., 1989; Alexander et al., 1996; Van Nest and Alexander, 1999; Lee et al., 2002), whose structure is based on two main subsystems, the Fire Weather Index (FWI) system (Van Wagner and Pickett, 1985; Van Wagner, 1987) and the Fire Behavior Prediction (FBP) system (Forestry Canada Fire Danger Group, 1992).

This paper will provide the conceptual derivation of the models of RISICO, also compared with those provided by CFFDRS. Besides, an analysis of the performance offered by RISICO is presented. In this connection, a comparison between the performance obtained by RISICO system and FWI, largely used in Europe, has been carried out.

The paper is organized as follows. In the next section, the general architecture of the developed system is introduced and the two main modules are discussed in detail. In the second section, a performance analysis of the overall system is presented. Finally, some concluding remarks are drawn.

The Structure of RISICO System

Following reasoning lines similar to those introduced by the developers of the CFFDRS, the general architecture of a system designed in order to assess the dynamic wildfire risk distribution could be represented as in Fig. 1. Different modules compose such a system, each of which represents a specific model. First, it is necessary to represent the dynamics relevant to the state variables associated with the fuel load, over the considered territory, as well as those related to the fuel moisture. In general, such dynamics refer to different fuel typologies (at least, dead and live fuel must be distinguished). Then, the potential fire spread model has to be considered in order to quantitatively describe the potential behavior of a wildfire front, in absence of any extinguishing action. Such a model is not used to obtain a forecast of the propagation process of a specific ignited fire, but only to evaluate the risk of spread after a possible ignition.

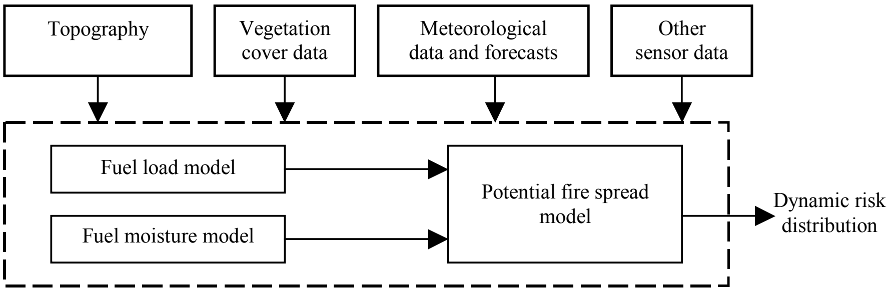

Figure 1— A schematic representation of the structure of a system designed in order to assess the dynamic wildfire risk distribution.

It is natural to use models discrete both in time and space. In this connection, 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 input data.

The information that feeds the various modules represented in Fig. 1 is partly static and partly dynamic. The first are related to topography, land use/vegetation cover data, which can be obtained from a data set stored in a Geographical Information System (GIS). As regards the dynamic information entering the system, it consists of meteorological data (provided by a network of ground sensors, such as rain gauges, anemometers, solar radiation sensors, etc.), and of meteorological forecasts (provided by a fine scale meteorological model), over a time horizon of suitable length. Besides, data coming from other sensors (ground or satellite based) may be available.

A suitable choice of the variables used to represent the wildland fire dynamic risk is that of using both the rate of spread and the linear intensity that a fire could assume in case of a successful ignition of the available fuel.

The conceptual scheme depicted in Fig.1 is quite general and may constitute the basis for the development of different schemes for the assessment of wildland fire risk. What such schemes are different in may be related to the definition of fuel classes and characteristics, to the mathematical structure of the models appearing in the figure, and to the values of the parameters of such models.

In the building of RISICO system, it has been chosen to consider, for any of the cells in which the territory is discretized, only two different layers along the vertical distribution of the fuel, namely live and fine dead fuel characterizing the considered cell. Moreover, for each classes of live and dead fuel, its load is assumed as constant, within a given seasonal period. Further, the moisture contents of each classes of live fuel is assumed constant (again, within a given seasonal period). Thus, only the moisture dynamics of fine dead fuel has to be represented. One can regard the above choices as oversimplifying, with respect to the complexity of the phenomenon to be modeled, but it must be noted that they are imposed by the structure of the available information about vegetation cover over the Italian territory. More important, it seems quite reasonable to attribute to fine dead fuel moisture dynamics the key role in fire ignition, at least as regards Mediterranean regions.

In the following two sections, the structure and the parameterization of the two dynamic models used by RISICO system are described.

The static information used in the present implementation of RISICO system refers to topographic and vegetation cover data. As regards topography, a Digital Elevation Model (DEM) defined over a 250x250 m regular grid produced by the Italian SGN (Servizio Geologico Nazionale and Row, 1994) has been utilized in order to represent the aspect and the slope of the Italian territory. As regards vegetation cover, information is drawn from CLC (CORINE Land Cover, 1994) map, which is able to provide information on land cover at a scale of 1:100000. Such a map, available as a grid file 100x100 m (CLC90 released in December 2000), uses a database including 44 categories, in accordance with standard European nomenclature, organized into five large classes: artificial surfaces, agricultural areas, forest and semi-natural areas, wetlands, water bodies.

For each seasonal period, and for those of the above 44 categories that can be interested by wildland fires, five parameters have been drawn from the literature (Anderson, 1982; Nunez-Regueira et al., 1999; Corpo Forestale dello Stato, 1985). Such parameters correspond to: a) for live fuel, load [kgm-2], HHV [kJkg-1], and moisture [%], b) for fine dead fuel, load and HHV. Thus, on the basis of the information provided by CLC map, such parameters are specified for any of the cells, and are generally different from one cell to another.

A thorough exploitation of the dynamic information provided by a LAM (actually the unique dynamic information used in the present configuration) is the main feature of RISICO system. In particular, the system receives daily from the Agenzia Regionale Protezione Ambiente in Bologna the outputs of the 00:00 UTC deterministic run of a meteorological non-hydrostatic Limited Area Model (LAM), namely Lokal Modell (Doms and Schättler, 1999). The information provided by the LAM consists of a set of data discretized in time steps of 3 hours over a time horizon of 72 hours, and defined over a rectangle made of a grid of 57200 regular cells of 0.05x0.05 degrees. The used meteorological variables are the 3-hour cumulated rainfall, $p()$, the air temperature, $T()$, the relative humidity, $\rho()$, and the wind speed/direction, $w()$.

The Fuel Moisture Model

Fuel moisture contents have a major effect on fire behavior owing to its influence on ignition and fuel combustion. Obviously, higher fuel moisture contents require a greater heat supply to dry the fuel before the combustion starts, and likewise slow down the fuel consumption rate (Marsden-Smedley and Catchpole, 1995). By contrast, lower moisture contents yield a greater fire intensity, spread rate and facility of ignition (Catchpole et al., 2001).

As indicated in the previous section, the only moisture dynamics that is considered is that relevant to fine dead fuel. In this connection, existing models are based on the assumption that the moisture contents of a particle of dead fuel, within a system with constant temperature and humidity, increase or decrease until, eventually, a value denoted as Equilibrium Moisture Contents (EMC) is reached. Such a value is a function of the temperature and relative humidity nearby the fuel

(Catchpole et al., 2001). Then, the basic model used in this paper to represent such a dynamic behavior is (Byram, 1959, 1963)

$$\frac{du(t)}{dt} = \frac{EMC - u(t)}{\tau} \tag{1}$$

where *u(t)* corresponds to the fuel moisture contents at time t, whereas *EMC* and τ are respectively the asymptotic value (Equilibrium Moisture Content) and the time constants of the first order system (1). The analytical solution of (1), can be discretized for each time step *n* assuming that *EMC* and τ are not time varying in the considered time interval

$$u(n) = EMC(n) + \left(u(n-1) - EMC(n)\right)\cdot e^{-\frac{\Delta t}{\tau(n)}} \qquad \text{if } p(n) \le p^* \tag{2}$$

$$u(n) = u(n-1) + p(n)\cdot\gamma_1\cdot e^{-\frac{\gamma_2}{(u_{sat}+1)-u(n-1)}}\cdot\left(1 - e^{-\frac{\gamma_3}{p(n)}}\right) \qquad \text{if } p(n) > p^* \tag{3}$$

where Δt is the length of the time interval, γ_i (i=1,..,3), are calibration parameters having suitable dimensions, u_{sat} is the saturation moisture, and p*[mm] is a threshold value for the cumulated rainfall.

The expression of EMC is identical to that used by CFFDRS (Van Wagner, 1977), in the dry phase, namely

$$EMC(n) = \alpha_1\cdot\rho(n)^{\alpha_2} + \alpha_3\cdot e^{\left(\frac{\rho(n)-100}{10}\right)} + \alpha_4\cdot\left(21.1 - T(n)\right)\cdot\left(1 - e^{-\alpha_5\cdot\rho(n)}\right) \tag{4}$$

where α_i (i=1,..,5), are calibration parameters having suitable dimensions.

Actually, in CFFDRS two distinct values of EMC are considered, namely one for the wetting phase and one for the drying phase, as different time constants are considered for the two phases. In the model considered in this paper such a distinction is not made, allowing an easier calibration phase, based on fuel stick data.

Concerning the dependence of the time constant, τ, on meteorological variables, the following structure, significantly different but simpler than the corresponding structure in CFFDRS, has been implemented in RISICO system

$$\tau(n) = \frac{\beta_0}{1 + \beta_1\cdot T(n)^{\beta_2} + \beta_3 w(n)^{\beta_4}} \tag{5}$$

where βi (i=1,..,4), are calibration parameters having suitable dimensions.

For the sake of simplicity, only the case T>0 has been considered.

Obviously, the behavior of the fuel moisture model is deeply impacted by the value of parameters α_i, (i=1,..,5), β_i, (i=1,..,4), γ_i, (i=1,..,3) and p*. An accurate calibration of such parameters has been performed by means of suitable parameter fitting techniques on the basis of a wide set of real data provided by a fuel stick sensor.

The Potential Fire Spread Model

Fire spread models may be generally classified within three broad categories: statistical models, semi-physical models, and physical models. In particular, semi-physical models seem to be the most suitable for the purposes of the present paper, since they do not require a deep physical modeling of the combustion phenomenon, yet are able to take into account the effect of macroscopic physical parameters and variables, like meteorological and topographical ones. For the purposes related to the design and implementation of RISICO system, a variety of models, already introduced in the literature (Rothermel, 1972; Drouet, 1974; Van Wagner, 1977; Albini, 1985), are available. The potential fire spread model used in RISICO system has been developed by following the same reasoning lines applied in the derivation of the above-mentioned semi-physical models, but taking into account that the objective is that of developing a tool to quantitatively determine the risk evolution over the whole national territory, rather than building a fire propagation model, providing the geometric dynamic behavior of the fire front. In particular, the choice made by the authors has been that of taking the basic structure of Drouet's model, but introducing some significant modifications, that are highlighted in the following.

To introduce the potential fire spread model structure used by RISICO, it is necessary to point out that it is based on information denoted as the nominal rate of spread, $v_{0,k}$, which is the rate of spread in the absence of wind, within a flat terrain. This quantity has a specific dependence on index k, which is representative of the particular cell considered. The nominal rate of spread, $v_{0,k}$, depends on cell index k, since it depends on the kind of fuel (i.e., particle size, bulk density, moisture, and chemical composition). In particular, it is assumed the following dependence by fuel load, d_k, and fuel moisture

$$v_{0,k}(n) = a_0 \cdot d_k \cdot e^{-\left(\frac{u_k(n)}{a_1}\right)^{a_2}} \tag{6}$$

where a_i (i=0,..,2), are calibration parameters having suitable dimensions.

On the basis of the nominal rate of spread, the potential rate of spread, at instant n and in cell k, which takes into account the influence of meteorological variables and of topography, is defined and determined as follows

$$v_k(n) = v_{0,k}(n) Z_k(n) \frac{W_k(n)}{N_k(n)} S_k \tag{7}$$

where:

$Z_k(n)$ is a correction [dimensionless] due to air temperature, with respect to a standard temperature (0°C);

$W_k(n)$ is a correction [dimensionless] due to wind speed on flat terrain;

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

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

The way such terms depend on real-time information is modeled as follows. Simplifying the expressions proposed by Drouet (1974), term $Z_k(n)$ and $W_k(n)$ in (7) can be obtained, as

$$Z_k(n) = e^{\gamma \tau_k(n)} \tag{8}$$

$$W_k(n) = \left\{1 + \delta_1 \left[\delta_2 + \tanh\left(\frac{w_k(n)}{\delta_3} - \delta_4\right)\right]\right\}\left[1 - \frac{w_k(n)}{\delta_5}\right] \tag{9}$$

respectively, where γ and δi (i=1,..,5) are parameters having suitable dimensions.

It can be shown that (9) corresponds to a function having a unique (absolute) maximum, attained, if one chooses the parameters values reported in Tab.5 in the next section, at $w_k(n)$=45 kmh^{-1}.

Wind speed has the most noticeable influence on fire behavior when the angle $\theta_k(n)$ between wind direction and cell aspect is null. Obviously, in the case of flat or weakly sloped terrain, the influence of wind speed on the rate of spread is independent of the cell aspect. On the other hand, in case of significant slope steepness, the angle between wind direction and cell aspect heavily influences the (potential) fire behaviour, in that, when θk(n) is about π, wind speed influence over the rate of spread has to be negligible. Thus, in order to represent the influence of topography on the effect of wind speed (represented via the correcting factor $W_k(n)$), in the model used by RISICO system term $N_k(n)$ has been introduced, as shown in (7). Such a term is given by

$$N_k(n) = 1 + \frac{2 s_k}{\pi}\left(W_k(n) - 1\right) e^{-\frac{(\theta_k(n)-\pi)^2}{2\varepsilon^2}} \tag{10}$$

where s_k is the slope steepness [rad], and ε is a parameter having suitable dimensions.

It is important to bear in mind that slope steepness has a twofold effect on fire propagation. In fact, in addition to conditioning wind effect on propagation as discussed above, slope steepness also has a direct effect, since the flames of a fire burning upslope are positioned closer to the fuels ahead of the fire. This dries and preheats the fuels at a greater rate than if they were on flat terrain. Thus, it is necessary to introduce term S_k in equation (7), representing the slope contribution to the rate of spread, and structured as follows

$$S_k = 1 + \lambda \, (2 \, s_k \, / \, \pi) \qquad (11)$$

where λ is a dimensionless parameter.

Having thus clarified the way to compute the potential rate of spread $v_k(n)$, which provides a quantification of the swiftness characterizing the (potential) spread of a fire, it is necessary to quantify also the intensity of the phenomenon. To this end, Byram's equation (1959) can be used to determine the (potential) fire linear intensity $I_k(n)$ [kWm^{-1}], namely

$$I_k(n) = v_k(n) \sum_{i=0}^{1} LHV_k^i \; d_k^i \qquad (12)$$

where d_k^0, (d_k^1) [kgm^{-2}] is the load of dead fuel (live fuel) for the season considered in cell k, whereas $LHV_k^0(n)$ and LHV_k^1 are the lower heating value [kJkg^{-1}] of the fine dead fuel and live fuel in cell k, in time instant n. Such heating values are given by

$$LHV_k^0(n) = HHV_k^0 \left[1 - \frac{u_k(n)}{100} \right] - Q \, \frac{u_k(n)}{100} \qquad (13)$$

$$LHV_k^1 = HHV_k^1 \left[1 - \frac{\tilde{u}_k}{100} \right] - Q \, \frac{\tilde{u}_k}{100} \qquad (14)$$

where, HHV_k^0, (HHV_k^1) is the higher heating value [kJkg^{-1}] of the fine dead fuel (live fuel), evaluated on the basis of the prevailing species composition in cell k, Q is the latent heating value [kJkg^{-1}], and $\tilde{u}_k$ is the moisture contents of live fuel in cell k (for the considered season).

Calibration and Validation of the Proposed System

The proposed system is based on the use of two different models, whose structure has been developed on the basis of semi-physical considerations. Such models are characterized by the presence of several parameters, which in general can hardly be associated to a definite physical meaning, and cannot be measured or estimated. Indeed, the most convenient way to attribute a sensible numerical value to such parameters is to find, possibly by means of repeated trials, an overall set of values that provides a satisfactory accordance between the dynamic risk forecast and the real observed data.

As mentioned in the previous paragraph, the calibration of the fuel moisture model parameters has been carried out on the basis of a time series of fuel stick data along with a data series of meteorological variables provided by ground sensors. Since data relevant to flammability are difficult to collect over a wide geographical scale and for a time interval of sufficient length, the most reliable and accessible real data are those related to actually detected fires. On the other hand, information related to detected fires is related to a multiplicity of aspects, not merely related to fire occurrence. Namely, for any fire, the available information regards the occurrence location, the time interval, the burnt area, the kind of vegetation mainly interested, the fire duration and, the extinguishing intervention carried out. The set of actual fires data, which have been used for the calibration/validation procedure, refers to 13992 wildland fires detected and suppressed over the Italian territory from January 1 2004 to December 31 2005 (Corpo Forestale dello Stato, 2006). Such fires have been partitioned in 4 different extension classes, namely Ei (i=1,..,4), on the basis of the reported burnt area S (see Tab.1). For each of such classes, an integral measure and an average value per fire of the information relevant to extension, duration, and extinguishing actions have been evaluated, and are reported in Tab. 1.

From Tab.1 one can observe that, in the considered time interval of two years, 13992 wildfires burnt 100980 hectares of woods and shrubs, which represent more than 1 % of the overall Italian wildland extension, namely 8675100 hectares (Corpo Forestale dello Stato, 1985). To face such an amount of emergencies, huge numbers of men and means were employed. On average, a team of about 15 firefighters working during about 5 hours was engaged on each fire, whereas the water bomber intervention was needed 1 to 3 wildfires. As one could expect, the higher the burnt area, the higher the average number of involved water bombers.

Table 1— *Integral and average values for several variables of interest relevant to the various extension classes.*

Class definition		*E_1 (S≤1ha)*	*E_2 (1ha<S≤10ha)*	*E_3 (10ha<S≤100ha)*	*E_4 (S>100 ha)*	*All classes*
Number of occurred fires		6704	5606	1564	118	13992
Burnt area S [ha]	*Integral value*	2537	21913	46171	30357	100980
	Average per fire	0.38	3.9	29.5	257.2	7.2
Fire duration [h]	*Integral value*	20486	34347	17294	4777	76904
	Average per fire	3	6.1	11	40.5	5.5
Overall duration of the extinguishing actions [h]	*Integral value*	16058	27508	15219	4674	63459
	Average per fire	2.4	4.9	9.7	39.6	4.53
Personnel involved in fire extinguishing actions [number of men]	*Integral value*	73020	88724	41257	8016	211017
	Average per fire	10.9	15.8	26.4	67.9	15.1
Water-bombers involved in fire extinguishing actions [number of missions]	*Integral value*	548	1575	1458	350	3931
	Average per fire	0.08	0.28	0.93	2.96	0.28

However, the overall number of water-bomber extinguishing interventions for fires belonging to the lowest extension classes is not negligible. This implies that a considerable amount of fires belonging to the lowest extension classes has been judged to be risky and therefore deserving an airborne intervention.

The information obtained from the analysis of really occurred fires has been compared with the information generated by RISICO and FWI. As regards the calibration/validation of the system, a risk assessment based only on the estimated values of the potential linear intensity $I_k(n)$ has been considered. In this connection, the difficulty of quantifying the degree of confidence attributable to linear intensity estimates suggests to base such an assessment on the definition of a suitable number of risk classes. To this end, 5 risk classes, namely R_j (j=0,..,4), have been defined (Tab.2). The boundary values of the linear intensity $I_k(n)$ have been adapted from those suggested by Rothermel (1983), aiming at taking into account the differences between typical fire dynamics in Mediterranean areas and in the areas considered by this author. A finer tuning of such boundary values is matter of further investigation. The definition of FWI risk classes is based on FWI ranges defined by Van Wagner (1987).

Table 2— *Classification of (potential) fires in 5 risk classes for RISICO system and FWI, respectively.*

	Risk Class	R_0	R_1	R_2	R_3	R_4
RISICO	Lower bound [kWm^{-1}]	0	86	345	900	1800
	Upper bound [kWm^{-1}]	86	345	900	1800	>1800
FWI	Lower bound Index value]	0	4	9	17	30
	Upper bound [Index value]	4	9	17	30	>30

Then, the following obvious question arises: is the distribution of the fire risk assessed by RISICO system consistent with the information corresponding to really occurred fires? To answer such a question, one must first define the meaning of the term "consistent" used above, bearing in mind that such a consistency is dependent upon the values of the parameters appearing in the fuel moisture, and the potential fire spread models. Then, let us collect the whole set of such parameters in a vector $\underline{\pi}$. Moreover, define, for any of the really occurred fires, the index risk j as corresponding to the highest risk class achieved (under the parameterization π) by the cell where the fire has occurred, during its whole duration. On this basis, it is possible to evaluate the numbers $n_{ij}(\pi)$, for i=1,..,4, j=0,..,4, of fires of extension class i that are characterized by an index risk j. Moreover, let us define $n_j(\pi)=\sum_{i=1}^{4} n_{ij}(\underline{\pi})$, namely the number of fires having index risk j.

Then, it is possible to define the following performance index

$$\Psi(\underline{\pi}) = \sum_{i=1}^{4}\sum_{j=0}^{4} \xi_{ij} n_{ij}(\underline{\pi}) \tag{15}$$

where ξ_{ij} are suitable dimensionless parameters. As regard the choice of the value of such parameters, one can reason as follows. First of all, the occurrence of fires, of whichever extension class, in cells characterized by risk class j, is to be penalized by letting ξ_{i0} =1 (i.e., the highest value), for any i =1,..,4. In fact, the occurrence of such fires is in itself an indicator of a poor performance, as no fire should have occurred if the risk assessment would have been correct. As regards the other coefficients ξ_{ij}, their value should be increasing with the number |i-j|, as a fire of a high extension class in a cell characterized by a low risk class has to be considered as an error, and vice versa (although the occurrence of a low extension class fire having a high risk index may be interpreted as a fire successfully and promptly contrasted). On this basis, the values reported in Tab. 3 have been selected as regards the coefficients appearing in (15).

***Table 3**— Values of parameters ξ_{ij}*

	j=0	*j=1*	*j=2*	*j=3*	*j=4*
i=1	1	0	0.2	0.4	0.8
i=2	1	0.8	0	0.4	0.6
i=3	1	1	0.4	0	0.2
i=4	1	1	0.6	0.2	0

The performance index $\Psi(\underline{\pi})$ so defined can be considered as representative of the quality of the forecast provided by the risk assessment system RISICO. Ideally, the optimum value of $\underline{\pi}$ should be such that $\Psi(\underline{\pi})=0$, but in practice this value cannot be attained. However, an extensive set of trials has been carried out in order to tune the parameters of the fuel moisture and the potential fire spread models, aiming at minimizing function $\Psi(\underline{\pi})$. The lowest value of Ψ that has been attained is 5326.8, which corresponds to the parameterization π reported in Tab. 4 and Tab. 5, whereas the value of Ψ obtained by FWI is 9296.8.

***Table 4**— List of parameter values for the fuel moisture model*

Model parameter	γ_1	γ_2	γ_3	α_1	α_2	α_3	α_4	α_5	β_0	β_1	β_2	β_3	β_4	u_{sat}	p^*[mm]
Value	6.5	12	3	1.88	0.481	7.25	0.238	0.115	20	0.004	2	0.002	0.65	50	0.1

***Table 5**— List of parameter values for the potential fire spread model*

Model parameter	a_0	a_1	a_2	ε	γ	λ	δ_1	δ_2	δ_3	δ_4	δ_5
Value	50	17.43	1.6	0.5	1.714×10^{-3}	2	1.5	0.848	16×10^{3}	1.25	25×10^{4}

Note, in passing, that, if the values of parameters ξ_{ij} would be all set to 1 when $i \neq j$, and 0 otherwise, the worst possible value of $\Psi(\underline{\pi})$ would be 13992, that is the overall number of fires, that is attained when every fire occurs in a cell having a classification different from the one of the fire. This may be useful to give significance to the obtained value $\Psi(\underline{\pi})$.

***Table 6**— The matrix **$[n_{i,j}(\pi^*)]$** for RISICO system (left) and FWI (right)*

	j=0	*j=1*	*j=2*	*j=3*	*j=4*
i=1	1004	1699	2451	1252	298
i=2	681	1373	2270	1066	216
i=3	107	305	661	400	91
i=4	3	26	47	31	11

	j=0	*j=1*	*j=2*	*j=3*	*j=4*
i=1	3099	640	1269	404	1292
i=2	2259	547	1144	389	1267
i=3	706	167	253	111	327
i=4	78	9	15	4	12

Moreover, by analyzing the matrix $[n_{i,j}(\underline{\pi})]$ reported in Tab. 6, one can observe that the most frequent "mistakes" for the RISICO system are those relevant to small extension fires occurred in cells classified with a high risk class, whereas FWI classifies more than 60% of big fires in the lowest class. With reference to RISICO system, the disagreement between forecasts and what has really occurred may be explained by various arguments. First, as previously mentioned, one can argue that a prompt fire fighting intervention may have reduced the impact of a fire that otherwise could have been particularly devastating. On the other hand, the risk classification of the cell could have been wrong (i.e., overestimated) owing to the poor performance of one of the used models. In this connection, it is the authors' opinion that the most critical model is the fuel moisture one. In fact, the present version of RISICO system uses a fuel moisture model uniquely based on fine dead fuel and referring to a kind of vegetation corresponding to 10-h time lag. On the other hand, FWI has been applied in its original version considering the three different oisture codes (FFMC, DMC, DC) without any calibration procedure. Besides, FWI is feed by temperature, relative humidity and wind speed provided by the meteorological model at time interval corresponding at noon (LST) and the cumulated rainfall during the previous 24 hours.

Further, the effectiveness of the developed system must be tested also from the viewpoint of the capability of identifying only a limited number of cells characterized by the higher risk classes. In fact, a system attributing, almost for every time interval, a high risk class to a very large percentage of cells in the Italian territory, would be of poor use in order to dispose the available (scarce) resources in order to be more ready to react to the incoming emergencies. In this connection, it is evident in Tab.7 that, under the selected parameterization, the average percentages (in the considered time interval), over the whole vegetated Italian territory, the percentage of area classified in R4 and R5 reach its maximum value of about 20% in the summer season.

Table 7— *The percentages of national vegetated area classified in each danger indexes j in the 4 seasons. Comparison between RISICO system and FWI.*

		j=0	*j=1*	*j=2*	*j=3*	*j=4*
Spring	RISICO	81.2	17.2	0.45	0.01	0
	FWI	66	12.5	13.2	6.9	1.1
Summer	RISICO	8.1	25.4	44.1	17.7	3.3
	FWI	33.8	9.1	15.6	21.7	19.6
Autumn	RISICO	72.8	17.9	5.6	0.7	0.07
	FWI	86.8	4.4	4.7	2.7	1.1
Winter	RISICO	60.6	34	4.8	0.4	0.09
	FWI	98.4	1.1	0.34	0.01	0

Conclusions and Further Research Directions

This paper has provided the structure and the application of a system that has been developed in order to provide a forecast of the wildland fire risk distribution over the Italian territory. A preliminary calibration/validation campaign has demonstrated the soundness of the proposed approach, which indeed is characterized by several similarities with approaches that have led to development of other dynamic risk assessment systems that are operational in other countries.

In the design of the proposed system, the best effort has been made by the authors in order to make the system well suited for the characteristics of the Italian territory, and capable of making the best use of all available (static and dynamic) information. On the counterpart, it is reasonable to expect that the approach here presented could be applied also to other geographical areas that have characteristics close to the Italian ones (like several Mediterranean regions).

The application of the proposed system over the whole Italian territory for two years has shown that the system is characterized by quite satisfactory performances as regards its capabilities of correctly identifying areas with higher or lower risk.

The preliminary calibration/validation, whose results are reported in this paper is only the starting point of a structured investigation aiming at determining the optimal parameterization of the adopted models, possibly making use of suitable mathematical programming techniques.

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