ELSEVIER

Safety Science 20 (1995) 61-70

safety science

Forest fire danger assessment methods and decision support

J.L. Wybo *, F. Guarniéri, B. Richard

Ecole des Mines de Paris, 06904 Sophia-Antipolis, France

Abstract

Forest fire danger is one of the main emergencies in many countries all over the world. To reduce the consequences, forest managers or fire officers use prevention, by reducing biomass, by locating fighting teams in exposed areas or by patrolling. To fight fire efficiently, they use suitable means: trucks, planes, helicopters, fire retardants. The keypoint of prevention and fighting is the assessment of danger, which can be done from different points of view and at different time scales: from historical data, by real time monitoring or by forecasting. A survey of operational danger rating methods shows two approaches: assessment of a global index, integrating several aspects of forest fires, or assessment of a set of indexes representing individually the key factors.

This paper describes a combination of assessment methods, integrated in a decision support system. Four methods are used, related to fire occurrence, assessing the frequency of fires from historical data, inflammability of dead fuels and live fuels, traducing the behaviour after ignition and fire severity, evaluating the difficulty of fighting. The integration of these methods is done using a knowledge-based approach in association with a relational database and a GIS.

1. Fire danger rating methods

1.1. Which approaches, which methods?

Each one of the existing methods refer to one or several aspects of wildfire problem, depending on the points of view and the aims that people have on forest fire. Therefore, forest fire danger assessment is described by two kinds of approaches which represent two aspects of fire management: hazard and requirement.

In the literature the words hazard and requirement have different meanings. Hazard includes both risk and danger components (risk is associated to prevention and ignition, danger corresponds to spread and fighting actions). Requirement takes into account the

* Corresponding author. Tel: +33 93 95 74 29. Fax: +33 93 65 43 04. E-mail: wybo@cemef.cma.fr.

SSDI 0925-7535(94)00067-0

notion of priority based on the environmental, social and human properties of an area concerned by forest fire.

The hazard point of view characterizes the fire in its phenomenon aspects and can be defined as a set of potentialities which group two kinds of factors: the parameters linked with fire occurrence (ignition frequency) and those associated to the fire spread and fighting. This approach describes the fire through ignition and spread mechanisms.

The occurrence and propagation parameters associate the fire events, their spatial density (which indicate the pressure on an area) and temporal evolution, human influence such as agricultural depression, land property, territory management, sensitive activities and physical aspects, such as slope, wind, or fuel flammability.

The differences between these methods, based on hazard, come from the levels of complexity and integration, the choice of the parameters (environmental factors, human factors), the tools and methodologies used, and the choice of the hazard components studied (ignition and/or spread).

The requirement approach corresponds to human life and patrimony threatened by fire, and considers the fire by its human, social and economic aspects. The requirement components include parameters such as the number of human lifes concerned (estimated from the density of population, housing), the value of patrimony and fight difficulties (road network, fire fighting equipments, topography, accessibility, distance to emergency centre). In other words, this approach considers the fire in relation with its close environment. It is a qualitative fire management; fire is not only seen as a phenomenon, but it is studied through the damage that it could induce. Behind this idea, is the concept of risk socialization. Territory managers have this view of forest fire, based on the requirements of protection and emergency priorities.

All methods which have been developed for forest fire assessment correspond either to the study of the fire components and its characteristics: ignition, spread, fight (French, American and Canadian methods are in this category), or to the study of fire by its human, social, and economical effects. In the following Section, a survey of methods corresponding to fire assessment methods is presented to introduce a new method for danger assessment, based on the forest manager points of view.

1.2. Literature review

The most commonly used definition of Fire Danger is the resultant often expressed as an index of both constant (fuel types, topography) and variable (weather conditions) danger factors which affect the ignition, spread and difficulty of control of fires and the damage they cause (Chandler et al., 1983).

Several countries have at different times set up various methods for forecasting the fire danger rating (Chandler et al., 1983), starting from a number of different assumptions, even though these have in general been based essentially on the consideration of meteorological factors. A synthesis of the main methods adopted and their particular structure is briefly presented.

The US method (The NFDRS, The National Fire Danger Rating System) is based on the mathematics and physics of fuel moisture and heat exchange as they affect fuel moisture variations (Deeming et al., 1972) and on laboratory experiments about the influence of various fuel and weather factors on fire behaviour (Rothermel, 1972). The NFDRS interprets the moisture level of a wide range of forest fuel sizes through the use of three representative classes of fuels with different drying states. It includes a fire rate of spread component and a component to represent the effect of long-term drying on the fuel. It also produces an index representing the fire intensity (BI, Burning Index) and it has a number of other indexes that can be used to indicate the level of other fire factors such as ignition possibility or rate of spread.

The Canadian method was largely developed from statistical analysis of large quantities of field data. The tables were empirically constructed by putting together weather, fuel moisture and fire behaviour data (provided by small test fires). Van Wagner (1974) describes this method which has been implemented on a computer by Kourtz (1980). The index is based on daily measurements of weather factors (wind speed, rainfall, temperature and relative humidity of the air) recorded at 12 a.m.

These authors consider that it is impossible to give a complete indication of fire danger rating for a given day only with one value. Based on the water content of three types of fuels, combined with the effect of the wind on the fire behaviour, this Fire Weather Index (FWI) is divided into six components:

— three primary sub-indexes representing the water content of a layer of forest bed and other light fuels (FFMC, Fine Fuel Moisture Code), the water content of a layer of compact organic matter (DMC, Duff Moisture Code) and the water content of a deep layer of compact organic matter (DC, Drought Code);

— two intermediary sub-indexes representing the rate of spread (ISI, Initial Spread Index) and the total quantity of fuel available for combustion (BUI, BuildUp Index);

— a final index representing the amount of energy produced per time unit and length unit of the flame front (FWI, Fire Weather Index).

The originality of the American and Canadian works is that they take into account different parameters from different components: fuels factors, human factors, and meteorological factors.

The Australian method was developed, as the Canadian one, from statistical analysis of large quantities of field data (McArthur, 1966a; McArthur, 1966b). McArthur designed a meter based on fire behaviour data measured after some 800 test fires with typical fuels. The tabulated indices have been reduced to equations (Noble et al., 1980) and programmed for use on a pocket calculator (Crane, 1982). This method is based on the consideration of the following parameters:

- fuel water content and its daily variation
- both open field and inside the wood wind speed
- fire rate of spread
- fuel load and its relation with the rate of spread
- slope
- height of flame as a function of: fuel moisture content, fuel load and wind speed.

Two indices are calculated. The first one is a cumulative index (based on evapotranspiration, rainfall and air temperature) providing the degree of inflammability of the fuel. The second one is an index that determines the level of fire danger, the speed of propagation and the difficulty of extinguishing the fire, and has a closed scale ranging between 0 and 100.

In France, a method based on the major weather factors and on empirical equations derived from experimental studies is used (Sol, 1992). The estimation of the risk level is based on meteorological forecasting and the actual system, developed by the National Weather Service. It includes weather parameters and soil water content. The risk value is described by five levels (low, moderate, medium, high, very high).

The Expergraph system (Wybo, 1992) integrates two methods. The first one, proposed by Carrega (1990), has been built from a statistical analysis of meteorological parameters during a collection of fires and proposes a combination of parameters closely related to fire occurrence. It has been initially elaborated for the French Riviera but turned out to be applicable in the entire south of France. The second method links, for each location, an estimation of the rate of spread with the time needed to reach it, in order to forecast the size of the fire to which the firefighters will be faced.

In former Soviet Union, the most widely used method is an index of fuel inflammability, which is a cumulative index calculated during the interval of days in which there has been no daily rainfall exceeding 2.5 mm (Nesterov, 1949).

Other approaches are based on forecasting methods adopted in Canada and the USA, integrating and modifying them according to the different conditions of climate and vegetation prevailing in the respective countries. Other authors, as Chuvieco (1989) use a danger index based on several parameters such as: vegetation, slope, exposure, distance to road and altitude. He does not assign an equal value to each parameter, but ponderates them according to their influence in the fire danger from expert judgments. The result is a formula which constitutes a risk index.

These global approaches, including the most important danger parameters, result in a risk integration which raises two difficulties: the first is related to the assessment of the relative coefficients of each aspect in the global index. The second difficulty comes from the melting of the original data which prevents the user from knowing the origin of the estimated value.

1.3. Points of view and Danger indexes

The main aim of this project is to provide users with an efficient set of data to support their decisions for forest fires prevention and fighting. To reach this goal, we have examined the different points of view that the experts have on forest fires. These points of view can be expressed as four questions:

— Is there any reason for a source of energy to be present? In other words, for each location, what is the probability for a fire event to occur ?

— Is the dead fuel dry enough to allow fire extension?

The starting point of fires is generally on the ground, as such, is the dead fuel on the ground dry enough to allow an extension of the initial energy?

— Is the live fuel dry enough to participate in the fire?

Once the dead fuel on the ground is burning, the fire will really expand if the live fuel is dry enough to burn and as such, increase the biomass involved and consequently the energy of the firefront.

— What is the energy to which firefighters are faced?

The difficulty of fighting a fire is directly related to the fireline intensity.

In terms of decision support, the first index corresponds to preventive methods, as patrolling and land management. The second and third indexes are used to estimate how the fire will propagate in real or simulated conditions. The fourth index corresponds to the needs of fighting teams to propose the appropriate means.

2. A combination of methods based on the danger levels

One key point of forest fire study and modelling is the difficulty and cost to collect the huge amount of data needed to describe the vegetation characteristics in details over an extended area.

In order to propose a solution to this problem, one of the goals of this project was to establish danger assessment methods using the minimum set of data and to validate the results on a test region near Athens: the Mount Parnis National Park.

Available information include a historic file of past fires, a topographic map and weather sensors, but nothing about vegetation.

It has been decided to establish vegetation models, representing the most common fuel complex and to build the corresponding map from aerial photo series and field validation. For each fuel model, sample plots have been studied to establish an average value of the parameters used in fire modelling and danger assessment.

This method is an interesting compromise as it is based on the experience of foresters to identify the fuel models to be distinguished.

2.1. Fire occurrency

To estimate the spatial density of fires in an area, we use a list of fire events, giving their date and location. First, we fix the period of time for which the fire events are processed, for instance the last five years. Then, we calculate all the distances between fires, we sort the results in classes and we determine the more frequent class, which distance is used for integration (This method presents the advantage to give the highest spatial precision with respect to existing data).

The next step is to create a map giving for each pixel the density of fire events: for each event of the list, we create a circle centred on its location and which radius is the distance used for integration. The density is for each pixel, proportional to the number of circles covering it. Fig. 1 shows the resulting map on the Mount Parnis area.

2.2. Average inflammability of dead FUELS

The Average Inflammability of Dead Fuels is derived from the estimation of the thin fuels (1 hr-timelag) moisture content, as they change under different meteorological conditions and during day and night hours. This index has also been considered as independent from the type of fuel model. Thus, this index has been estimated by the two following steps:

Step 1: estimate the fine fuel moisture content from tables as they have been proposed by Botehlo (1993). The relative humidity and the temperature during day and night are the meteorological parameters which have been considered in these tables. Correction factors

Fig. 1. The resulting map on the Mount Parnis area.

are applied, according to the different hours of the day and night as well as for the amount of rainfall per week.

Step 2: classify the values of the fine fuel moisture content in terms of four average inflammability levels: low, medium, high, very high.

2.3. *Average inflammability of live fuels*

The average inflammability of live fuels is derived from the estimation of the inflammability of live fuels of all the fuel models. The fuel models which are considered here are those represented in the Mount Parnis area, but this method can be extended to other models. The estimation of this danger index was done in four steps:

Step 1: Two inflammability indexes were given to each one of the understory species of the fuel types of Mont Parnis. These indexes express the inflammability level of species during summer, and more specifically the first one gives the inflammability level for the months May, June and July (early summer) and the second, for August, September and October.

The selection of these indexes was done by Valette (1990) according to flammability studies done on species of southern France which are similar to those of Mount Parnis.

Step 2: The average inflammability index of each fuel model was estimated by the following way:

- evaluate the volume (coverage × cover) of each species,
- multiply the volume by the inflammability indexes (early/late summer),
- make the sum of all the species, in order to associate one index to each fuel model.

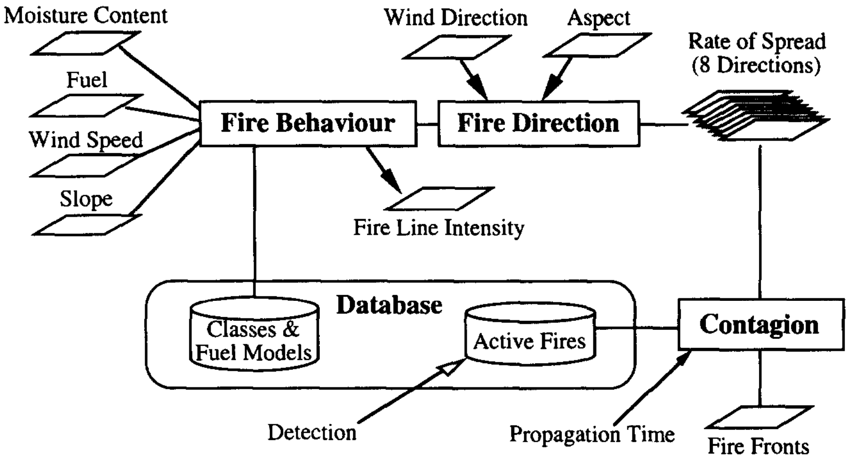

Fig. 2. Simulation of fire behaviour.

Step 3: The number of classes and the class limits were determined according to the values of the fuel models indexes and also to the needs (of detailed estimation). Four inflammability classes were created.

Step 4: Finally, each fuel was classified in terms of the average inflammability of its live fuels during summer period (early and late).

2.4. *Fire severity*

The fireline intensity is the parameter considered for the Fire Severity estimation. The interpretation of this parameter is best related to the prediction of severe fire behaviour (Rothermel, 1983).

The steps to estimate this danger parameter were the following:

Step 1: Both fuels characteristics and meteorological parameters were considered. From the fuel models of Mt Parnis and the relative humidity and temperature, the fireline intensity was calculated as one of the outputs when applying Rothermel's model and especially BEHAVE equations, in order to predict the rate of spread and to forecast fire propagation, as shown in Fig. 2.

Step 2: Four classes of fire severity have been created from the values of fireline intensity derived from the above calculations, based on the classification given by Rothermel (1983).

3. Knowledge-based fire risk assessment

To plan and manage forest fires effectively, both accurate and appropriate data for modelling information is needed. In addition, this information must be easily maintained and updated to incorporate current information from a variety of sources. Geographic Information Systems (GIS) correspond to these goals and current applications incorporating GIS technology have clearly illustrated its importance and viability as a mechanism for improving program management and short-term decision making. So it appears that GIS have a significant impact on the quality and the effectiveness of forest management. Data base layers containing Mount Parnis' slope, topography and vegetation characteristics were collected and input into the GIS database.

In order to increase the performances of the GIS we have linked this tool with a knowledge base system: the EXPERTPLAN system (Wybo, 1992), which is used to estimate the danger indexes. The knowledge formalism consists of production rules, wherein expert knowledge is expressed as a series of independent statements with each statement being encoded as an independent condition–conclusion pair. This formalism is the most commonly used declarative representation in operational expert systems.

After collecting knowledge and writing the corresponding set of rules (in a text file, using a small set of symbols), it is necessary to build a knowledge base which can be used for deductions. To do this, we have designed a rule compiler. Its role is to verify the syntax of the rules and to build the knowledge base which contains parameters, rules and relations; i.e., which parameters are conditions in a rule, which rules conclude on a parameter.

Once a knowledge base has been designed and tested with EXPERTPLAN, it is necessary to describe (in data base tables) the characteristics of the parameters: constant value or map, value, name of the map. It is also necessary to associate to each parameter a set of classes. These classes represent all the possible values for a parameter. They are associated to colours for the display.

When all these specifications are ready, EXPERTCARTE (Wybo, 1992), a second knowledge base system designed to manage raster maps, assesses the maps of the four Danger Rating Indexes presented above, as shown in Fig. 3. To achieve this task, the maps of input parameters, used in the deductions, have to be available in the GIS.

During a deduction session, EXPERTCARTE updates (pixel by pixel) the maps of the deduced parameters. After the deductions, all the output parameters (which have a map format) are updated in the GIS and their versions (date and time of update) are also updated in the data base.

The main characteristics of this knowledge base system are:

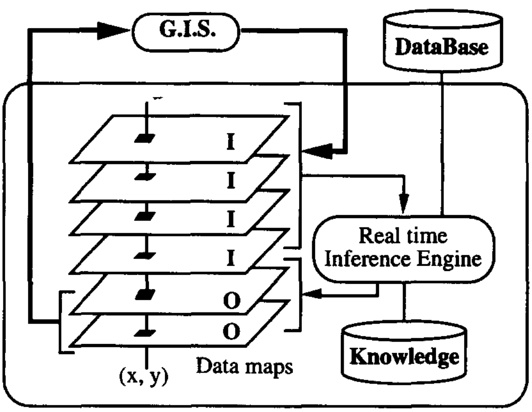

Fig. 3. the EXPERTCARTE system.

- data are represented as raster maps (one per parameter of the knowledge base),
- there is no direct interface with the user, and
- it has the ability to interact with the Data base Management System and the GIS.

In fact, from the knowledge base name with which it shall work and as from then, EXPERTCARTE loads the parameters (present in the knowledge base) characteristics from the database. These characteristics include the format of data (raster map, constant value), the version (update time) and the set of classes describing all the possible values of each parameter (which will appear as different colours on display).

4. Conclusion

The integration of danger rating methods in a decision support system gives to managers a powerful tool for decision making, if two conditions are achieved: update these data by monitoring the situation and allow experts to create and update their own methods.

Automatic acquisition of data is essential to danger assessment in the sense that managers must be aware of the situation and its evolution but, to be fully efficient, this automation has been extended to the management of data processing and danger indexes updating.

The study presented in this paper is part of the FMIS system (Wybo and Meunier, 1993), developed in the frame of an EEC research project. It has been designed to meet these requirements by associating autonomous processing and knowledge-based assessment of data. This system has been demonstrated on October 1993 in Athens and presented to forest managers. The four indexes give to the users a precise idea of the danger level in the different aspects of wildfires, as they represent their different points of view.

This information can be used for prevention tasks, for instance to start patrolling in most sensitive areas; it can also be used to help decision making when fire events occur.

References

Botehlo, H., 1993. Rules for day time and night time fine fuel moisture content prediction. UTAD, internal report, Portugal.

Carrega, P., 1990. Climatology and index of forest fire hazard in Mediterranean France. Proc. Int. Conf. on Forest Fire Research, Coimbra, Portugal.

Chandler, C., Cheney, P., Thomas, P., Trabaud, L. and Williams, D., 1983. Fire in Forestry, Vol. 1: Forest Fire Behaviour and Effects. Wiley, NY.

Chuvieco, E., 1989. Congalton R.G. Application of Remote Sensing and GIS to Forest Fire Hazard Mapping Remote Sensing in Environment, No. 29.

Crane, W., 1982. Computing grassland and forest fire behaviour, relative humidity and drought index by pocket calculator. Aust. For.

Deeming, J.E. et al., 1972. National Fire Danger Rating System. US For. Serv. Res. Paper RM-84, 165 pp.

Kourtz, P.H., 1980. A calculator programme for the Canadian Forest Fire Weather Index Environ. Can. For. Serv., Petawawa Nat. For. Inst., Inf., Inf. Rep. PI-X-3; 10 pp.

McArthur, A.G.B., 1966. (a) Forest fire danger meter, MK4. For. and Timber Bur For. Res. Dist. Canberra.

McArthur, A.G.B., 1966. (b) Weather and grassland fire behaviour Aust. For. and Timber Bur. Canberra. Leaflet No. 100.

Nesterov, V., 1949. Combustibility of the Forest and Methods for its Determination. USSR State Industry Press.

Noble, I.R. et al., 1980. McArthur's fire-danger meters expressed as equations. Aust. J. Ecol., 5: 201-203.

Rothermel, R.C., 1972. A mathematical model for predicting fire spread in wildland fuels. USDA Forest Service, General Technical Report INT-115, Intermountain Forest and Range Experiment Station.

Rothermel, R.C., 1983. How to predict the spread and the intensity of forest and range fires. USDA Forest Service, General Technical Report INT-143, Intermountain Forest and Range Experiment Station.

Sol, B., 1992. Indice météorologique de risque d'incendie: recherches en cours et prévues en France. Revue d'analyse spatiale quantitative et appliquée, No. 32, Nice, France.

Valette, J.C., 1990. Inflammabilité des espèces forestières méditerranéennes. Conséquences sur la combustibilité des formations forestières. Revue Forestière Française.

Van Wagner, C.E., 1974. Structure of the canadian forest fire weather index. Can. Dept. Environment., Can. For. Serv. Pub. 1333, 44 pp.

Wybo, J.L., 1992. EXPERTGRAPH: Knowledge based analysis and real time monitoring of spatial data, application to forest fire prevention in French Riviera. Proc. Int. Emergency Management and Engineering Conf.: Managing Risk with Computer Simulation, Orlando, FL.

Wybo, J.L. and Meunier, E., 1993. Architecture of a decision support system for forest fire prevention and fighting. Proc. Int. Emergency Management and Engineering Conference: Research and applications, Sullivan, Arlington, VA.