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A Decision Support System for Forest Fire Management

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Abstract

Forest fires are considered natural phenomena but the magnitude of the problem can be attributed to poor forest management and to the extreme weather conditions. Furthermore, the abolishment of traditional activities related to forests has sent away people from the forests that they used to protect them. The aforementioned reasons result in the annual destruction of large forest areas, agricultural cultivations, industries, animals and even human lives. At the same time, catastrophic floods entail the gradual desolation of the affected areas and large amounts of carbon dioxide along with smoke particles aggravate air quality.

In the present paper, a Decision Support System is proposed capable to support policy makers and services to counteract wildfires destruction danger in lowland Pine forests. The system is composed of two major components: (a) A Wildfire Destruction Danger Index useful for preventive and suppressive measures planning and decision policy making and (b) a Forest Management Planning Decision Support System useful for fire risk reduction through forest management plan. The open architecture of the system allows incorporation of data coming from external sources e.g. satellite systems, meteorological stations etc. All its subsystems can stand alone so as to satisfy the needs of responsible organisations (peripheral institutions of fire brigade, forest inspection and local authorities). The proposed system can be both used as an intergraded operational tool in forest fire management and as a training tool for personnel of various services involved.

Keywords: Wildfires; forest management; decision support systems; expert systems; geographic information systems.

1. Introduction

During the last decades, forest fires have increased in numbers and intensity in the European Union and especially to the Mediterranean region member States. The magnitude of the problem can be attributed to the increasing demand for land and to the occurrence of extreme weather conditions, e.g. hot and dry periods in combination with strong winds. Furthermore, regarding Greece, the abolishment of traditional activities related to forest such as resin tapping, in combination with the general trend of population concentration to the urban areas has distanced people from the forests that they used to protect.

In order to confront forest fire phenomenon new methods and integrated models have been developed for fire management. More specifically, subsystems have been developed such as Fire Simulators, Fire Danger Rating Indexes, and many research activities are in progress that are referred to remote surveillance and mapping of forests and forest fuels [Rothermel, (1972); Byram, (1973); VanWagner, (1977); Andrews and Rothermel, (1982), Carega, (1991); Viegas, (1997); Viegas et Al., (1999); Kaloudis et Al, (2001); Kaloudis et Al, (2003)].

In this work we describe a Forest Fire Management Information System (FFMIS) based on expertise of forestry, telecommunication and information systems. That system had been proposed recently from a research group aiming to design and implement a Decision Support System capable to support policy makers and Services to counteract wildfires destruction danger in lowland forests [Karteris et Al. (2002)]. The objective of the proposed system lies in the introduction of technological support towards the detection and suppression of forest fires in early stage because their extent and climate conditions render impossible their control and confrontation. The implementation of a fire management plan assumes the participation of different public services and of many people from different expertise as well as individuals. Due to this, the FFMIS must be able to operate in different enterprise environments and satisfy specific needs for each one e.g. forest fuel management for Forest Service and management of fire fighting means and personnel for Fire Brigade. Therefore, various levels of users must be able to run it as an integrated system and in separate modules.

The structure of this paper includes a short description of the FFMIS and proceeds to a full analysis of its two main components: A WildFire Destruction Danger Index (WFDDI), useful for policy making and preventive-suppressive measures planning and a Forest Management Planning System (FMPS). It should be mentioned that the proposed system is of open architecture in order to be able to combine data coming from satellite systems or other external sources. Uncertainty is present both in forest factors values and in forest functions modelling. Fuel characteristics are an example of a factor incorporating a degree of uncertainty. Other factors like soil erosion, production potential or climate characteristics contain also o degree of uncertainty or vagueness. Due to this, artificial intelligent methods and specifically fuzzy logic is proposed as the main reasoning mechanism to handle uncertainty [Zadeh, (1965); Zadeh, (1973); Zadeh, (1990)].

2. System's architecture

The proposed FFMIS consists of several subsystems. These systems contain recent research results gained in the fields of forestry, informatics and telecommunications. More specifically the FFMIS will be comprised of the following subsystems:

1. A Decision Support System including:
   a) A WildFire Destruction Danger Index (WFDDI), useful for policy making and preventive-suppressive measures planning.
   b) A Forest Management Planning System (FMPS) for forest biomass (fuel) management.
   c) A Fire Fighting Means and Personnel Management System, for effective management of means, planning of fires extinguishes and personnel training.
2. User Communication Subsystem and,
3. An Early Fire Detection Subsystem, for forest observation and on time detection of fires.

FFMIS will be functioning as a tool of the executive authorities responsible for coordination of forest fire units management. Furthermore, some of the subsystems will be also able to operate as stand-alone systems to cover remote end user needs (e.g. units in the field).

2.1 The Decision Support System

It will utilize methods of Operation Research in Business Planning as well as in tactical level during the confrontation of forest fires incidents. The results of the processing of the multi-criteria system will supply the Knowledge Base of the corresponding subsystem and vice versa. The estimation of the parameter values of the factors required for the multicriteria models will be supported by the Knowledge Management System. The Knowledge Management subsystem will include data and text mining tools using as main sources the systems Warehouse and Database.

One of the most important characteristics is that a component that extracts conclusions, independent from the type of chain cogitation, deals with uncertain data requiring fuzzy logic. System's databases include the following types of data:

- Analytic geographic maps of the region that is under system's surveillance,
- Meteorological data (temperature, humidity, winds etc.) that rise the fire,
- The ground morphology,
- The type of forest vegetation,
- Statistical elements of previous fires and,
- Scenarios for alternative fire expansions based on different climatological and ground conditions.

An important subsystem of the DSS is the Information Control and Management subsystem. This system provides the essential equipment activated from the monitoring section and from other exterior information collecting systems. Communication with the detection devices takes place either via constant network or via radio links. The management system is connected with a database that contains information relative with the:

- Mapping of the area of supervision
- Equipment of surveillance-detection and
- Possible scenarios of confrontation depending the fact

There is also an application server where the essential software and applications, which serve the communication between the users and the management system, are installed. The application server communicates with the database in which there is stored information relative to the:

- Users of the system
- User profiles and
- Communication scenarios

2.2 User Communication Subsystem

The User Communication Subsystem (UCS) provides with the necessary information at an official level (information to the fire confrontation centre) and, also, in a personal level (information to forest fire-fighters, surveillance teams). UCS also provides with information central management of the coordination centre via screen connected with the application server. This mechanism is monitoring the area under surveillance in real time and allows communication via internet and a network of mobile telephony.

2.3 Early Fire Detection Subsystem

The Early Fire Detection Subsystem (EFDS) is a forest area surveillance mechanism locating and monitoring fires. The surveillance-localization equipment is constituted of:

- Surveillance cameras,
- A fire detection unit and,
- Energy collection systems for autonomous operation of the equipment.

The main goal of EFDS is the precise location of fire from the moment it appears. Fire detection signals are transmitted to the information management subsystem, where further activities are decided via the decision reception subsystem. Continuous surveillance of the forest area via a closed circuit television allows continuous fire progress attendance. In case of fire, after information infiltration by the reception decision subsystem, the responsible personnel are automatically notified. Notification takes place through portable devices (mobile telephones, PDA) that support SMS, MMS messages. The personnel can send messages via their portable devices to the system requesting additional information. This bidirectional communication system via SMS, MMS, is encoded in order to avoid usual time-consuming process of sending a message.

3. Wildfire Destruction Danger Index (WFDDI)

WFDDI component is dedicated to calculate the future threat from wildfire for long and short term and for small or large areas. It provides the WFDDI values before any treatment and for every combination of proposed treatments. It also calculates the WFDDI, for each treatment combination at specific time intervals according to the predicted changes of vegetation composition and structure. This information is useful for the determination of fuel management. WFDDI values are used by the rest of system components.

In practice, it is impossible to know the precise time and location of a future wildfire or the behaviour of the fire and the objects in threat. For a given period, however, it is possible to estimate the expected fire risk of an area, which can be based on the following parameters:

1. Probability of Fire Incidence
2. Fire severity
3. Probability of a specific Fire Severity
4. Values in Threat
5. Sensitivity of Values in Fire

These parameters are considered for the development of a composite WildFire Destruction Danger Index (WFDDI). Fire Incidence Probability (FIP): To compute FIP of a site, one parameter is Fire Incidence History. It is concerned with fire incidences and can be considered as constant for a certain period. This parameter can be computed for a major area X and the result value can be used in sub-areas of X. This parameter incorporates two cases, that a fire either breaks out in the given area or it is driven in it by the wind from some neighbourhood area. Fire transfer depends on the: distance between the two areas, the relative altitude position of the two areas, the direction and speed of wind and the existence of obstacles in the fire route, such as the fuel brakes. However, changes in human presence and behaviour should also be considered in the computation of FIP. Hence, two more parameters are the change rate of the human population and the change rate of the income per capita. They represent the varying part for the computation of FIP.

Fire Severity (FS): It represents the magnitude of a fire event or a class of fires and thus the difficulty of the fire to be extinguished and consequently the size of threat to the objects. For the calculation of fire severity in the present work, four main fire behaviour parameters have been chosen,

- Fire Type

- Flame Length
- Fire Line Intensity and
- Rate of Spread

The above parameters can be calculated from existing fire behaviour simulation models [Byram, (1959); Rothermel, (1972); VanWagner, (1977); Andrews and Rothermel, (1982)]. The input data of a simulator are environmental parameters, i.e. topography (slope, aspect), fuel characteristics (load, composition, structure, and humidity) and meteorological conditions (air humidity and temperature, precipitation, wind direction and velocity and sunshine duration). Topographic data can be obtained from Digital Elevation Models (DEM) and they can be considered constant for long periods of time. Future fuel characteristics can be obtained from models of Forest Vegetation Evolution. Finally, weather conditions can actually be substituted by climatic observations of long time intervals. According to the World Meteorological Organisation (WMO) climatic observations of at least thirty years are needed in order to obtain representative climatic data.

Probability of a specific Fire Severity (PFS): It represents the probability for a certain FS to occur in a certain period of time in a given area. FSP values can be calculated either for a certain period of a year (e.g. months with high fire activity) or for the whole year. Hence, comparisons are possible between identical periods. Since the calculation of FS values requires climatic data, the calculation of a reliable FSP requires climatic data from a long succession of years.

Values in Threat (VT): These are values of objects and environmental entities. They can be classified into two categories, forest objects, such as timber, fruits etc. and non-forest objects, such as, human lives, public infrastructure etc. The objects themselves, beyond their physical presence and their contribution to the evolution of a fire, may have a commercial value. On the other hand, environmental entities such as the aesthetics of a landscape do not have a direct commercial value. Hence, two values in threat can be distinguished, the commercial and the utility value. The estimation of the probable size and shape of an area that can be burnt and thus the estimation of the threatened values for each case can be based on the simulation of the fire behaviour, the starting location of the fire and the obstacles that can have an impact on the route of a fire. It can be measured in qualitative fuzzy values e.g. high, medium and low.

Sensitivity of Values in Fire (SVF): This parameter concerns the estimation of the loss of the value of an object from a fire. A fire does not necessarily cause the complete loss of the value of an object but can decrease it. The loss of this value depends on the sensitivity of the object to fire. An estimation of it can be based on the physicochemical properties of the object and on the fire behaviour.

4. Forest Management Planning Subsystem

In forest management decision process are used data concerning the primitive (forest data) and derived (forest metadata) factors values. Forest data can directly be measured while forest metadata can be calculated by the use of models. Forest metadata, which are necessary for forest management planning are the:

1. Timber and Non-Timber Production: this provides the potential forest ability to produce forest and non-forest products to each location. This is used to decide the main and secondary objectives of forest management and treatments selection.
2. Soil Erodibility Index: this provides the soil risk and hence the limitations related to soil erosion, to apply the various kinds of treatments.
3. Wildfire Destruction Danger Index (mentioned above): this provides the wildfire risk and thus the necessity for taking wildfire protection measures. Its values also used to evaluate the effectiveness of the proposed management treatments to reduce wildfire risk.
4. Wildfire Characteristics: These are data related to wildfire behaviour under various weather, fuel and topographic conditions. These used to for the calculation of WFDDI values. It also used to suggest and evaluate fuel treatments intensity.

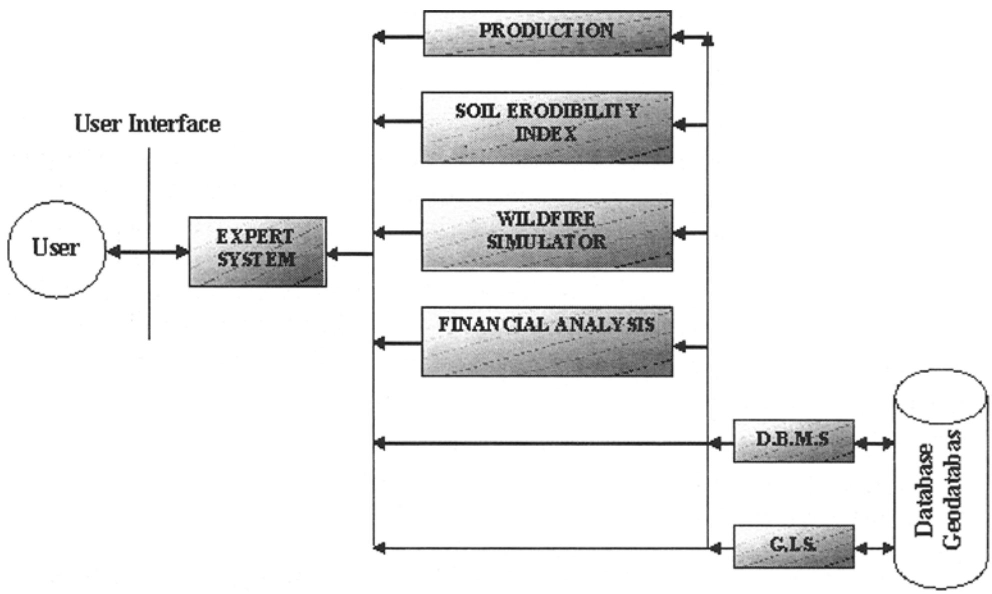

***Figure 1.** Architecture of the Forest Management Planning Decision Support System*

A DSS for forest management planning must incorporates a decision module (Expert System) to manage the domain knowledge and modules able to provide the above mentioned forest metadata. Moreover, it must incorporate components for store and retrieval of factors values. To keep and retrieve the values of factors valid all over the forest (global factors), databases and a Database Management System (D.B.M.S) are needed. Factors with spatially variable values (local factors) are kept in Geodatabases and retrieved by a Geographic Information System (G.I.S). Except the technical parity of the system, it must also provide financially correct solutions. Due to this, a Financial Analysis module is necessary to evaluate the financial impact of the different solutions and make the cost benefit analysis. The aforementioned modules for automation reasons must be integrated in one system (fig. 1). The relationships and interaction between them are described as follows:

Data Base/Data Base Management System (D.B.M.S): It keeps global factor values, such as, climatic, fuel models, human and animal populations, development characteristics, financial data etc. It retrieves the existing values of global factors and provides the results to the other modules.

Geodatabase/Geographic Information System (G.I.S): It contains local factor values, such as topographic data, vegetation characteristics, forest biomass load, soil characteristics, and site quality index. GIS also makes the necessary spatial calculations. It provides data to the expert system, to the derived factors calculators and to the financial analysis module. It also keeps informed the maps and the corresponded databases with the system results (proposed treatments and values of local factors), for future use, user information and comparative studies.

Production Module: This evaluates the production potential of a site and determines which products, in what quantity and quality it can produce. It calculates the quantity and quality of the products at the beginning of the system run and after the final synthesis of the proposed treatments. It provides its results to the expert system.

Wildfire Simulator: This based on the well-known wildfire behaviour simulation models [Rothermel (1972); Van Wagner (1997); Alexander (1988)]. It has forward and backward functionality. During forward functionality, calculates wildfire characteristics such as Wildfire Type, Rate of Spread, Flame length, Wildfire Intensity. During backward functionality, calculates the necessary degree of fuels treatments to lower wildfire characteristics e.g. the amount of slash removal and so to reduce the size of the WFDDI to accepted levels.

Soil Erodibility Index: It calculates the Soil Erodibility Index for each location and also calculates the Soil Erodibility Index for each suggested combination of treatments.

Expert System: It makes final decisions about primary and secondary forest management objectives, treatments combination and their application intensity. It provides the final consultation. The Expert system makes extensive use of fuzzy logic techniques during the decision process; it can provide non-fuzzy consultation, which is more tangible by the end users, thanks to defuzzification process. The Expert System follows an automatic order of targets satisfaction e.g., when WFDDI is high, it gives priority to reduce the WFDDI values against other targets like financial one. This order is determined according to local conditions (Local factors values). The user can also intervene by asking the system to follow a customized order.

4.1 Uncertainty

It is a common understanding that in all real world situations the available information is always imperfect, incomplete, vague and often erroneous. The fact remains though, that such imprecisely defined classes play an important role in human thinking, particularly in the domains of pattern recognition, communication of information and abstraction (Zadeh, 1965). Working on environmental subjects, there are many manifestations of uncertainty and fuzziness due to natural phenomena. For example, it is almost impossible using today's techniques to measure fuel humidity accurately over extended areas, since the conditions that affect it vary temporally and locationally (understory, sunlight intensity - duration, wind velocity, atmospheric humidity etc.). To monitor therefore fuel humidity over large areas, a prohibitively great number of measurements must be taken for a long period. In practice, therefore, approximations of fuel humidity levels are accepted. The same is also true for other variables, such as fuels load. There are also other reasons of uncertainty, such as the inability to predict the time and position of a future fire event.

It is also fuzziness, which is present in many situations related to space and time. For example, forest density changes gradually either from one position to another or in time. In many cases, therefore, it is rather impossible to define exactly where or when the forest changes from dense to thin.

Uncertainty in fire management can be attributed to:

- The lack of data over extended forested areas, and/or long time intervals.
- The errors in measurements of forest factors values.
- The poor modelling of forest functions due to their complexity. For example, forest stand structure is difficult to be modelled accurately. Hence, future values of some forest factors are considered in approximation.
- The inability to predict accurately the frequency, intensity, time and position of future fire events.

To be therefore realistically operational, Information Systems must contain mechanisms to optimally exploit this inexact and eventually vague information, as well as to elicit it from the user or the domain expert. Hence, various formal models aim at transforming this type of data into usable knowledge. One solution is the incorporation of fuzzy set theory.

5. *Discussion-conclusions*

Effective fire management planning can greatly be facilitated by integrated information systems. The advantages of such systems are that they:

- Can store and retrieve tedious amount of data and perform various type calculations in a very sort time.
- Exchange information with other systems or humans in real time.

The practical advantage of such information is that preventive and suppressive measures can be taken according to the expected size of fire damages. Such measures include fuel modification for fire behaviour alternation, construction of fuel brakes (e.g. between forest and residence places and public infrastructure), establishment of fire detection networks and fire-fighting plans, move forces to the areas with high risk.

The majority of ecological knowledge incorporates a degree of fuzziness and uncertainty, which are difficult to be removed because they form inevitable or inherent parts of the ecosystem [Kampichler et Al. 2000]. Therefore, any improvement on models cannot provide greater accuracy than that in the input data [McBratney and Odeh (1997)]. Fuzzy models will not increase the accuracy of the results beyond the existing knowledge and the quality of data [Rykiel, (1989)], but they will enable constructing models, wherever it is otherwise impossible, or they will improve the behaviour and flexibility of existing models. Fuzzy models can be used for the representation and processing of non-linear relationships by the selection of the right number of fuzzy sets and adaptation of their intervals. Fuzzy logic uses concepts similar to the human thought, making easier the transformation of existing knowledge into models, and reducing drastically the number of combinations of factors. It also facilitates data collection by the use of fuzzy values.

The proposed Fire Management Planning System uses fuzzy set theory for the representation and management of uncertainty. It facilitates fire management planning by integrating various models and methodologies in one modular system. Its usefulness is profound, for short and long-term fire management planning, since it provides information about the current and future level of fire risk and determines appropriate measures that should be applied. Used as a scenario simulation environment, it can also minimize undesirable side effects caused by the application of precaution measures.

The expected results of the proposed system are:
At operational level:

- Prevention of fires through securing deterrent measures, which minimize risks and causes of fire generation.
- In time detection and formation of a plan for the management of fire with continuous supervision.
- Management and allocation of resources and means so that is ensured their optimum exploitation.
- Development of plans and alternative scenarios that would ensure the direct confrontation of potential incidents with the minimum implication to the environment, the least possible risk for human lives and the minimum cost.
- Evaluation of operational plans through simulation processes and exercises.

At tactical level:

- Implementation of scenarios and solutions during the occurrence of the event, in order to effectively confront it (minimization of risk of human lives and minimization of negative repercussions in the environment and in the economic activities).
- Programme and application of periodically scenarios practices to avoid fires. These scenarios and more general measures of prevention are adapted dynamically in accordance to prevailing conditions (weather, locations, bas-relief, good of forest, etc).
- Training of executives and forces of forest firefighters.
- Organization of special informative programmes and actions of behaviour for the sensitisation and activation of involved institutions and various social groups.

Up to now some of the system components have already been implemented (e.g. WFDDI, and part of the Forest Management DSS). In the framework of this system, trials will take place in selected areas in order to validate system operation. Given that venturousness that characterizes lowlands of northern Evia, this area is considered as the most suitable field of trials.

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