

# Review of state-of-the-art decision support systems (DSSs) for prevention and suppression of forest fires

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**Abstract** Forest ecosystems are our priceless natural resource and are a key component of the global carbon budget. Forest fires can be a hazard to the viability and sustainable management of forests with consequences for natural and cultural environments, economies, and the life quality of local and regional populations. Thus, the selection of strategies to manage forest fires, while considering both functional and economic efficiency, is of primary importance. The use of decision support systems (DSSs) by managers of forest fires has rapidly increased. This has strengthened capacity to prevent and suppress forest fires while protecting human lives and property. DSSs are a tool that can benefit incident management and decision making and policy, especially for emergencies such as natural disasters. In this study we reviewed state-of-the-art DSSs that use: database management systems and mathematical/economic algorithms for spatial optimization of firefighting forces; forest fire simulators and satellite technology for

immediate detection and prediction of evolution of forest fires; GIS platforms that incorporate several tools to manipulate, process and analyze geographic data and develop strategic and operational plans.

**Keywords** Decision support systems · Fire behavior simulation · Forest fires · Geographic information system · Mathematical algorithms · Risk management

## Introduction

Forest ecosystems are our priceless natural resource and are fundamental to the global carbon budget (IPCC 2007). Forests contain approximately 66% of the surface carbon and have potential to sequester increasing amounts of CO<sub>2</sub> through time (Lu et al. 2006).

Destructive and recurrent forest fires (of high intensity) are one of the greatest hazards for the viability and sustainable development of forests, and have impacts on natural and cultural environments, and the economy and the quality of life of local and regional populations. Forest management can be focused on prevention of destructive forest fires with the objective of retaining stored carbon and contributing to the mitigation of climate change impacts from the CO<sub>2</sub> emissions which result from large forest fires (Hurteau et al. 2008).

Forest fires can stem from either natural (lightning) or anthropogenic causes (carelessness, accidents, arson). Anthropogenic fires typically account for the greatest percentage of forest fires, especially in the Mediterranean region (Ager et al. 2014; Carmel et al. 2009; Christopoulou 2011; Demir et al. 2009; Dimitrakopoulos et al. 2011; Moreno 2014). In Greece, natural causes account for 2.2% of all wildfires, whereas anthropogenic causes account for 95% (35% derived from unknown/random reasons; 35%

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from negligence; 25% from intent<sup>1</sup>). Forest fires annually affect 1% of the global total forest area (Christopoulou 2011).

At the European Union (EU) level, for the reference year 2011, 55,543 fires affected a total of 269,081 ha of forest. During 2011 in Greece, 1613 forest fires (3% of all forest fires occurred in the 5 most vulnerable<sup>2</sup> regions of the EU) burned 29,144 ha<sup>3</sup> of forest (11% of the overall burnt area of the same 5 most vulnerable regions). Eighty-nine of the forest fires in Greece burned more than 40 ha and, in total, burned 36,872 ha. From 1983 to 2008, fires in Greece burned 1,361,312 ha, for an annual average of 52,358 ha; 1465 fire incidents, and fire intensity approaching 36 ha per incident (Tsagari et al. 2011). The area affected by forest fires covering more than 40 ha, corresponds to forests (45%), protected natural areas (29%) and farmland (26%). Unfortunately, 32% (11,849 ha) of the overall damaged land in 2011 affected areas that are part of the NATURA 2000 network (European Commission 2012b).

An annual average of 9.3 million ha were burned in Russia between 1996 and 2005, while in Canada 2 million ha are affected by fire annually (for the last four decades) (Flannigan et al. 2009).

Van der Werf et al. (2010) estimated the average global emissions from fires to be 2.0 Pg C per year for approximately 22 years (1997–2009). The greatest amount of emissions originated from Africa (52%), followed by South America (15%), equatorial Asia (10%), the boreal region (9%), and Australia (7%). They also estimated that the major contribution to global fire carbon emissions derived from fires in grasslands and savannas (44%), woodland (16%) and forests (15%) (ibid.).

In future, climate change could affect drought frequency and intensity, with follow-on impacts on fire frequency and intensity. Due to the increased demand for forest goods, there is potential for greater CO<sub>2</sub> emissions perturbing even further the global carbon budget (Williams et al. 2007).

According to Lu et al. (2006), the mean annual carbon release caused by forest fires in China amounts to over 11 Tg per year. China is a large country and as a result, is characterized by spatial variability in the number and size of forest fires due to different local characteristics (e.g., climatic conditions, forest fuel) (Lu et al. 2006).

On a smaller spatial scale, the five Mediterranean countries of Greece, Spain, France, Portugal and Italy on

average produce estimated annual CO<sub>2</sub> emissions ranging from 358,509 to 5,816,367 Mg CO<sub>2</sub> (Vilen and Fernandes 2011). In a study using the *Forest Carbon and Emissions Model* (FCEM) to analyze the impact of four (2007) catastrophic fires in California (USA) on greenhouse gas emissions and opportunities to prevent and adverse environmental and climate impacts, Bonnicksen (2008) estimated that these wildfires burned over 586 km<sup>2</sup> of forestland and emitted an estimated 9.5 million tons of greenhouse gases, without taking into account the post-fire impacts. This means that if the decay process after fires were considered, the estimated total emissions could reach 38 million tons of greenhouse gases (Bonnicksen 2008).

From a financial perspective, Greece in 2007 suffered a destructive fire event and losses (affecting about 500,000 people) were estimated at 1.91€ to 3€ billion (Mitsakis et al. 2014). In Wales, the economic cost from grass fires reached 4.5£ million (Forestry Commission 2014). In Turkey in 1999, forest fire damage cost about US\$10 million (European Commission 2014), demonstrating the economic impact but not addressing the social cost (e.g., loss of human lives).

From a socioeconomic standpoint, forest fires can have multiple impacts on the structure of society. The following statistical data highlight the significance of such impacts. Rabade and Aragoneses (2008) reported that during 1991–2003 in Spain, fires caused 59 people to be fatally injured and 118 people to be wounded, while there were occasions of massive evacuations relocating 41,752 people. Further, 169 dwellings were strongly or slightly affected by forest fires. Major problems resulted for electricity and water supply networks, while several road segments were blocked due to direct and indirect forest fire impacts (ibid.). Morton et al. (2003) listed wildfire impacts from 10 case studies in USA. Fire impacts included: the financial cost for fire suppression, which ranged from US\$ 120,000 to 150 million; the destruction of more than 130 dwellings; the loss of protected areas for valuable species of flora and fauna; damage to large numbers of public facilities and infrastructure; evacuation incidents of thousands of people; reduced tourist arrivals and income to service providers; timber damage; cultural and archaeological locations and premises were damaged and require restoration and resources; and health impacts due to smoke that affected millions of people (Morton et al. 2003). Canadian citizens have experienced similar consequences with costly damage to infrastructure and premises. Around 33% of particulate matter (PM) emissions are derived from forest fires (University of Alberta 2006).

For the above reasons, the selection of strategies to manage forest fire, while taking into consideration both functional and economic efficiency, is of primary importance. To this end, several versions of DSSs are fully

<sup>1</sup> For instance, forest fires could stem from “land use conflicts, political reasons or terrorist acts, complex proprietary regimes, shepherds and accumulated flammable forest material” (Christopoulou 2011).

<sup>2</sup> Portugal, Spain, France, Italy and Greece.

<sup>3</sup> The share of forest land corresponds to 19,348 ha and the share of non-forest land amounts to 9796 ha (European Commission 2012b).

integrated with GIS platforms that incorporate tools to manipulate, process and analyze geographic data. Some DSSs are totally web-based and include forest fire simulators and satellite technology tools for immediate detection and prediction of evolution of forest fires. Others are constructed on database management systems and/or mathematical or economic algorithms for spatial optimization purposes, so that they can support fire managers. Use of DSSs enhances the capacity of fire managers to prevent and suppress forest fires and reduce their impacts on natural and built environments and on human life.

## Characteristics of DSSs and their contribution to global forest fire management

### Structural elements of DSSs

DSSs are valuable tools for prevention and management of forest fires and are globally adopted at growing rates. The basic models-subsystems which comprise the structural elements for managing forest fires, and most DSSs use, are the following (Bonazountas et al. 2007; Dimopoulou and Giannikos 2004; European Commission 2012a; Giovando et al. 2013; Glasa 2009; Gumusay and Sahin 2009; Kalabokidis et al. 2012; Keramitsoglou et al. 2004; Lee et al. 2002, 2010; Noonan-Wright et al. 2011; Wybo 1998):

- Retrieval, analysis, update, edit and prediction models of geospatial (geomorphology—topography, socioeconomic and environmental data), meteorological and satellite data,
- Risk indexes and thematic maps (past fire incidents, moisture data) of indigenous vegetation and forest fuel,
- Fire propagation and behavior models and
- Use of interactive programs for the preparation, planning, coordination and prompt dispatch of forces of fire departments (human force, number and kind of fire machinery—land or aerial forces or even a combination).

### DSSs based on database management systems and mathematical/economic algorithms

One of the first DSSs to exploit the usage of several technological tools and the precursor of the subsequent and technologically advanced DSSs for prevention and fighting of forest fires is the application of Wybo (1998). The key in that system is that the DSS incorporates in its databases a certain number of pre-processed scenarios which correspond to specific fire incidents. This eliminates the need to compose new scenarios from scratch, if, for example, new meteorological data are received. Hence, valuable time is

saved during the process of monitoring, management and fighting of each fire incident in real time. Furthermore, this system contains integrated feedback, where the manager has the ability to produce or modify/update the pre-existing scenarios (according to new input). The new scenarios can, in turn, be applied to similar fire incidents in future. The subsystem of this DSS might divide the case study into smaller and specific subareas on the basis of fire risk level and the desired protection level of each identified district according to its local characteristics (for example the ecological value) (Wybo 1998). A given area can be divided into Fire Management Units, each with its own prescribed management strategy. This feature tailors responses to natural conditions while improving organization and management of information. This is especially useful when there are complex site conditions such as high biodiversity, difficulties in management of forest fuel. The importance of forming fire management units is obvious, especially in cases where fires cross more than one administrative region. This policy is used in USA, where it is referred to as *Unified Command*: (1) general aims and priorities are determined; (2) confrontation strategies and alternative solutions are established; (3) better coordination among agencies is targeted; (4) the best usage and allocation of available forces is achieved. All the above, including the avoidance of overlap between agencies saves resources and improves the effectiveness of fighting similar fire incidents (National Interagency Fire Center 2013).

Dimopoulou and Giannikos (2004) used an integrated system for forest fire control. This consisted of a geographic information system (GIS) module, a mathematical programming (MP) module, and a simulation model. A database provided the necessary spatial information. The optimal allocation of the fire department units (including amounts and types of forces) is estimated so that the fire-fighting authorities will be prepared to locate the fire and act within 10 min (time limit based on international standards) to any possible forest fire. Afterwards, the model of fire behavior “sends” new input, which is based on fire evolution (e.g., fire engines not available, natural barriers across main roads), to the subsystem of mathematical programming, enabling managers to deploy available fire-fighting resources within a specified time limit (Dimopoulou and Giannikos 2004).

Bonazountas et al. (2007) improved on the basic structural elements of DSS by adopting an additional model of socioeconomic factors (e.g., demography, tourism). These factors could affect the combustion risk levels. A thematic map is an output of this model. The probabilistic model contributes to the process, so that managers could plan the best allocation of the resources (firemen, land and aerial fire engines). An effectiveness analysis is carried out of the resources (human force, number and type of fire

machinery, estimation of the time needed for fire brigades to reach the fire). Moreover, restrictions such as topography, strong winds, low visibility due to smoke, or the limits of economic resources are taken into account and the aims and strategies are adjusted accordingly. Another useful component of this model is estimation of economic cost for the maintenance of fire infrastructure and the fire mission, and for the overall burnt area. This is combined with an additional index which incorporates the land values of fire unit. Hence, it is possible to adopt specific management for particular geographical zones (Bonazountas et al. 2007).

Mavsar et al. (2012) reviewed the economic theory governing four fire management DSSs used in America and Europe. They used the “theoretical foundations of the efficiency analysis” of fire management measures to investigate the DSSs models’ level of performance. They investigated the following four DSSs models: (1) Leopards model (Canada), (2) Kitral model (Chile), (3) Sinami model (Spain) and (4) Fire Program Analysis—FPA (USA). Of the four DSSs models they reviewed, the Sinami model based on  $C + NVC^4$  was considered the best, since it helps fire managers perform an economic analysis of their investments (e.g., fire resources spatial allocation efficiency). The Sinami model incorporates economic impacts of fires (both negative and positive) in the stream of products and services generated from forest lands (Mavsar et al. 2012).

### DSSs based on fire behavior simulators

The foundation of fire simulation lies in Rothermel’s (1972) mathematical models for estimating fire spread. He also developed models for predicting crown fire behavior (Rothermel 1991). These fire models are integral parts of many contemporary fire simulation models such as *Farsite*, highlighting their contribution and significance to forest fire science.

*Farsite* is a deterministic fire simulation software that uses the principles of the “*elliptical growth model of forest fire fronts*” developed by Richards (1990). *Farsite* has three main uses: simulation of past fires, simulation of active fires, and simulation of potential fires. Analysis of past fires shows how the simulator reproduces known fire growth patterns, which is crucial in building confidence for using the simulator to project growth of active fires (Finney 1994). Fire behavior models included in *Farsite* calculate surface and crown fire behaviors as well as fire acceleration, spotting from torching fires, and fuel moisture (Finney 1998). Since *Farsite* relies on the outputs of the above

subsystems, the fire polygon is expanded beginning from an ignition point which is evolved according to the influence of wind and slope dimensions as well as the fire spread rate and time step. Geomorphological, meteorological, fuels and wind characteristics of the study area constitute the primary inputs of the model. Fire perimeters, fire spread and intensity are the main outputs of each simulation (Finney 2004). Many applications of *Farsite* have been implemented in different areas with the adjustments needed for local characteristics and for a number of specific purposes such as the influence of a fuel treatment process in fire evolution (Arca et al. 2007; Mutlu et al. 2008; Ryu et al. 2007; Schmidt et al. 2008; Stephens 1998; Stratton 2004).

Other researchers developed fire simulation systems using the Cellular Automata (CA) techniques. The primary inputs (topography, fuels characteristics and meteorological data) of these models and the previously mentioned fire behavior systems are quite similar. Karafyllidis and Thanailakis (1997) created such a model in a hypothetical mosaic of homogenous and heterogeneous fuels and they concluded that their model outputs closely resembled fire evolution in real situations. Improved versions of the Karafyllidis and Thanailakis (1997) model for more realistic representation of fire propagation were developed by Berjak and Hearne (2002) and Hernandez Encinas et al. (2007).

Yassemi et al. (2008) developed a fire behavior system that combined GIS capabilities with CA techniques. The degree of efficiency was considered highly satisfactory, since the *Prometheus* simulation (the Canadian fire growth model) results were comparable with the proposed—GIS and CA—model (Yassemi et al. 2008). Using a different approach, Vakalis et al. (2004a, b) used fuzzy logic and neural network modeling techniques in a mountainous area of Greece to estimate fire spread.

*Prometheus* is a deterministic fire simulation model which relies on the principles of the *elliptical growth model* of Richards (1990) and can be a valuable tool for rational and effective analysis and decision making. The primary inputs are derived from the geomorphology of the study area; the fuel types; the meteorological variables, and the corresponding Fire Weather Index System (FWI) values. The fire growth simulation is based on the Canadian Forest Fire Behavior Prediction System (CFFBPS) which permits the extended application of the model across the entire country. In addition, through this model, everybody may discover any piece of information related to the fire simulation, such as fire perimeter, rate of speed, surface and crown fuel consumption, fire intensity, or flame length. This detailed database is important, and all points on maps are attached with all the necessary information for burned and unburned areas as well as all the

<sup>4</sup>  $C + NVC$ : Financial cost (prevention and suppression planning expenditures) + net value among destructive and beneficial implications of forest fires (Mavsar et al. 2012).



corresponding features (Tymstra et al. 2010). *Prometheus* fire growth model has been applied in many projects primarily focusing on the Canadian territory due to the matching of fuels with the CFFBPS (Tymstra et al. 2007; Yassemi et al. 2008).

Burn-P3 is a fire model that simulates and reckons the fire probability of huge fires. The model aims to assess the “*relative likelihood of burn probability*” for each geographical element of the study area, using the burn probability of pixels on given raster landscapes. This is realized by simulating the ignition point as well as the spread of every independent large fire. This software demands many inputs for efficient prediction. The inputs include fuel, topography, ignition points, fire zones (different fire regimes), weather zones, wind characteristics and the layer of firebreaks. Except for the spatial units, the model is structured with some environment requirements such as season; ignition cause; length of burn, and the daily fire weather characteristics.<sup>5</sup> In addition to the burn probability (number of times each pixel affected by fire divided by the total number of fire simulations), Burn-P3 can produce supplementary outputs such as the size of the fires which took place at the simulation process; the ignition point geographically determined; the season; the number of spread-event days, as well as the area and the corresponding fuels burned (Western Partnership for Wildland Fire Science 2014). Burn-P3 software has been applied to many places in Canada (Beverly et al. 2009; Brown et al. 2010; Parisien et al. 2005, 2011, 2013). Burn-P3 relies on local (Canadian fuel database) fuel information because there is direct association of estimated fire behavior with each fuel type in the CFFBPS (Forestry Canada 1992; Hirsch 1996).

### DSSs based on geographical information systems platforms

#### *DSSs focused on Dijkstra’s algorithm and network analysis*

Dijkstra’s algorithm (1959) is used to find the shortest path between two points and has many applications in a variety of fields. Dijkstra’s algorithm was widely applied in forest fire simulations because, according to natural laws, a fire must follow a route which demands the minimum time. The reasoning is based on the fact that fire will ignite the nearest fuel as it evolves along the forest surface (Kourtz et al. 1977). Later, Lopes et al. (1995) combined the Rothermel’s fire spread model with Dijkstra’s algorithm in order to estimate fire propagation in mountainous topography.

<sup>5</sup> In addition to meteorological observations, Burn-P3 exploits the FWI System as developed by Van Wagner (1987).

One of the most widespread applications of Dijkstra’s algorithm is network analysis,<sup>6</sup> which commonly refers to road network characteristics. Many researchers have explored the optimal (shortest) path mainly for transportation and emergency purposes (Kai et al. 2014; Sui and Wang 2012; Rees 2004; Zhan 1997). Examples are finding shortest distances between fires and fire agencies to minimize time in transit (Hatfield et al. 2008). Dijkstra’s algorithm has been improved to enhance the efficiency of the initial algorithm (Fan and Shi 2010; Rodriguez-Puente and Lazo-Cortes 2013).

Akay et al. (2011) combined the advantages of GIS and DSS and applied Network Analysis which incorporated four measures. First is identification of the nearest fire unit and estimation of the fastest route between each fire unit and the fire incident. The fire team taking the shortest route and the shortest time to arrival is activated (Condorelli and Mussumeci 2010; Gumusay and Sahin 2009; Keramitsoglou et al. 2004). Second, the quickest route of each moving fire team is estimated in real time and if a barrier appears across a pre-chosen route (e.g., a landslide), a second-best alternative route is determined at the same time from the current point of every responding vehicle to the site of the fire (Condorelli and Mussumeci 2010; Ichoua et al. 2000; Keenan 2008). The third measure involves the spatial coverage (through buffering) of forest land from the current fire units. The key to this method is the critical time of response by each fire team to approach the district of fire. If this combination is inadequate (both in travel distance and time of response), then it is concluded that more fire brigades must be established, so that every possibility of fire spreading and its consequences may be limited. The fourth measure involves fire teams using aircraft (helicopter) because they cover areas inaccessible to land-based teams (Akay et al. 2011).

#### *DSSs focused on fire risk determination*

In Brazil, a valuable Web DSS was developed by Barbosa et al. (2010). It included fire hotspot locating services using satellite technology (locating sites that surpass 47 °C). It also enabled the development of vulnerability maps that consider the fire risk caused by anthropogenic or natural causes as well as the determination of fire spread factors (fuels, topography). The output of this map consists of several thematic maps such as land-use maps, topographic maps (slope and aspect), minimum and maximum temperature and humidity maps, rainfall, wind velocity and wind direction maps. Next, a process of risk assessment

<sup>6</sup> Network Analysis Toolbox is fully integrated into GIS. The most of the applications of network analysis toolbox are relied on the Dijkstra’s algorithm.

was followed, based on the contribution of the above characteristics to fire ignition and spread. Each characteristic was assigned to five risk levels (very low to very high) depending on the nature of the characteristic (the changeable fire risk level was depicted on each thematic map). Afterwards, an algorithm reckoned the risk degree of each geographic area and integrated the estimated risk levels into one final risk map. Finally, when a fire breaks out, this point is immediately assigned to the respective fire alarm which coincides with the pre-estimated risk level. The appropriate land and/or aerial forces are mobilized directly (according to the significance of a given fire alarm) resulting in faster response to fire incidents before they spread (Barbosa et al. 2010).

Focusing on the Euro-Mediterranean countries, Kalabokidis et al. (2012) developed an integrated DSS (*AUTO-HAZARD PRO DSS*) that incorporates four components meteorology, geomorphology, automatic ignitions detection, and fire behavior based on study area characteristics (e.g., fuels). The first three components represent the index of fire ignition and, when the latter is paired with the index of fire behavior, produce the final fire risk index which incorporates the basic elements of fire environment in any area. The product of this procedure consists of six separate thematic maps and one integrated map, which is a valuable tool for the simulation process as well as for operational vigilance, effective prevention, and timely suppression of forest fires (Kalabokidis et al. 2012).

Due to the complexity of the spatial nature of events like forest fires, other researchers used multi-criteria analysis and decision making methods. They combined, for instance, Knowledge Discovery in Databases (KDD), artificial neural network, or fuzzy logic techniques with Analytical Hierarchy Process (AHP) and other multi-criteria evaluation techniques through GIS platforms. Their objective was to address spatially explicit, complicated problems and determine the potential forest fire risk (Chen et al. 2003, 2004; Dong et al. 2006; Iliadis et al. 2002; Jaiswal et al. 2002; Kaloudis et al. 2005; Lapucci et al. 2005; Power 2006; Sakellariou et al. 2015; Sharma et al. 2012; Temiz and Tecim 2009; Vadrevu et al. 2010).

Several methods for estimating forest fire risk are available. Many researchers compile spatial data derived either from agencies or satellite sources that relate to natural factors like fuel types and characteristics; topography; and anthropogenic factors such as proximity to urban and road networks. Afterwards, the relationship of each factor with fire risk is estimated (internal weighting) and finally, an external weighting is based on the degree of influence of each dimension on fire ignition and evolution. The overlay of these factors through GIS (multi-criteria analysis) yields a fire risk map for any given area (Dong et al. 2006; Jaiswal et al. 2002; Power 2006; Sakellariou et al. 2015).

Other authors have used similar methods incorporating fuzzy logic techniques to deal with uncertainties that are inherent to forest fires. Kaloudis et al. (2005) developed a fire risk index considering the following factors: *fire incidence probability; fire intensity; fire severity probability; values at risk and sensitivity of values at risk*. Iliadis et al. (2002) developed a fire risk classification of the administrative parts of Greece based on real fire statistics using fuzzy logic techniques. Sharma et al. (2012) used all the natural and anthropogenic factors mentioned above with AHP techniques for efficient forest fire risk determination.

#### *DSSs focused on fire risk assessment and immediate fire incident management*

According to Thompson and Calkin (2011) and Thompson et al. (2011, 2012), fire risk is rendered in mathematical terms by the equation:  $E(NVC_j) = \sum p(f_i)RF_j(f_i)$ , where “Net Value Change” (NVC) of each resource is calculated as the sum of burn possibilities multiplied by the “response function” of resource per fire intensity level.<sup>7</sup> The corresponding detrimental or beneficial fire implications are reckoned in quantitative terms. Due to the fact that the quantification of certain types of resources (mainly natural resources) is often subjective, a second best solution is adopted. The (local) experts systems substitutes the determination of fire effects on resources without wasting valuable time in calculating complex reactions (reaction of each fuel type to fire effects) and as a result, strategies and tactics are adjusted according to the current conditions, and the optimum reaction scenario is chosen. Thus, negative repercussions are minimized in a timely manner. Instead of the NVC method, a “Total Change Equivalent” method is applied in which the affected area (ha) is estimated either destructively or beneficially. A drawback of this method is that it does not take into consideration the social preferences and agency priorities. To this end, multi-criteria analysis techniques are used to fill this analytical gap and each resource is assigned and weighted according to its relative significance (ibid.).

At larger geographic scale, especially the adopted DSS in the USA is of interest. *Wildland Fire Decision Support*

<sup>7</sup> With the term Net Value Change (NVC) is defined the percentage change of each resource from the initial condition against fire effects. That is, some types of resources may be adjusted better than others against fires, so the fire implications may be either beneficial or detrimental in the long run. So, the equation elements define the burn probability of each pixel of any possible fire intensity level (conducting by a fire behavior simulation model), as well as the “response” of each resource against fire effects for any fire intensity level (an index that can be estimated by experts’ systems). Finally, NVC is computed by the sum of the above equation for all potential fire intensity levels (Thompson and Calkin 2011; Thompson et al. 2011, 2012).

*System* (WFDSS) is an interactive web-based system that includes fire modeling subsystems and economic tools to facilitate and optimize the decision making process during forest fires events (WFDSS 2016). The comparative advantage of the WFDSS is the integration of all previous management processes of wildfires into a unified system that can access all essential data and has additional tools for fiscal evaluation of past fire incidents. All procedures are manageable in real time, while they are supported directly via the internet from many agencies responsible for managing forest fires. Besides the basic structural elements of DSSs, WFDSS incorporates additional economic and environmental tools. In addition, risk assessment of crucial structures (natural resources and infrastructure<sup>8</sup>) is conducted and these resources are depicted in the fire evolution map based on fire intensity. The “Net Value Change” might be either beneficial or destructive, depending on fire intensity and the resource nature, and can be estimated if protection of high-value resources might call for aggressive suppression. Otherwise, agencies may control and use the fire effects for environmental purposes. The first fundamental element of this DSS is the fire simulation system (*FSPro*) which maps fire evolution, utilizing the “Minimum Travel Time Algorithm” in real time when needed.<sup>9</sup> Mapped concentric circles present the predicted fire evolution possibilities in percentages. A crucial component of WFDSS is known as *RAVAR* (Risk Assessment of Values At Risk). *RAVAR* uses geospatial data, fire evolution and behavior predictions in combination with infrastructure locations to protect natural and cultural resources. *RAVAR* produces a comparative economic analysis so that the best possible scenario from environmental and socioeconomic perspective can be chosen. Finally, there are special tools which calculate concentrations of particulate matter  $PM_{2.5}$  and ozone for the estimation of air quality impacts. Other modules develop thematic maps depicting the orbit of smoke and its implications on human health (Calkin et al. 2011a, b; Noonan-Wright et al. 2011).

At a similar geographical scale, the EU information system (*EFFIS*—European Forest Fire Information System) includes several innovative and valuable functions. *EFFIS* maps areas damaged by forest fires greater than 30 ha in area. This enables assessment of the extent and type of these catastrophes. *EFFIS* information is land-sourced rather than remotely sensed. The significance is apparent when natural barriers (cloudy weather) or technical restrictions preclude retrieval of satellite images and

location of active fire hotspots. *EFFIS* information is collected using a *Rich Site Summary* (RSS) method from several EU sources (Google news, blogs) at various geographical levels. A filtering and automatic geocoding procedure are conducted and each fire incident is located geographically. When *EFFIS* is combined with *IDAS* (*IDAS* provide information on population size and density, spatial allocation of infrastructure, and protected area locations) they offer capacity for comparative assessment of different forest fire incidents that occurred simultaneously in remote geographic locations. This enables managers to better prioritized fire firefighting resources based on population size and the amount and kind of infrastructure at risk (Giovando et al. 2013).

## Discussion

The combination of operational research models and GIS enables management of the growing spectrum of complicated problems with massive and complex datasets. The use of GIS and new vehicle routing modules in DSSs can contribute to effective decision making (Condorelli and Mussumeci 2010; Ichoua et al. 2000; Keenan 2008). These technological advances have been successfully adopted by the *Network Analysis* tool and it is integrated into GIS platform and may contribute to more efficient fire management in future.

DSSs use not only GIS, but also satellite technology tools such as *LiDAR*, a reliable tool for rapid measurement and survey of vegetation characteristics, resulting in quicker and more effective management of fires; better post-fire recovery planning; ecosystem rehabilitation; restoration and the saving of fiscal resources (Wing et al. 2010).

A new technique is emerging, which is serving the same target of maximization of environmental safety and sound financial management and requires the active participation of citizens. Local geographical information is provided by citizens on a voluntary basis (*VGI*—Volunteered Geographic Information). This is an additional tool in crisis management that uses geospatial data in real time and provided by non-specialist users using devices such as smart phones or GPS receivers. Dissemination of information is conducted via internet. This tool can serve as an additional data source, supplementing satellite imagery and other online (internet) sources that are integrated in *EFFIS*. This can maximize overall system effectiveness (De Longueville et al. 2010).

DSSs can contribute to the quantification of complex interactions which take place during suppression of a forest fire and can facilitate the timely handling of critical situations. The positive key points of DSSs combined with

<sup>8</sup> Crucial structures and natural resources: Human settlements, transport, energy, oil and telecommunications infrastructure, habitat with endangered species, historical monuments) (Noonan-Wright et al. 2011).

<sup>9</sup> So that the strategy and tactics to be adjusted according to the current conditions in any given area.

management expertise can moderate the impacts of forest fires on the natural and cultural environment, and to the economic impact of every fire suppression mission (Mavsar et al. 2012).

DSSs are integrated information systems that incorporate state-of-the-art structural functions to help prevent and suppress forest fires. DSSs as an analytical and operational tool contributes to the mitigation of certain types of uncertainty which are involved in forest fires phenomenon. According to Thompson and Calkin (2011), such uncertainties could be referred to as *linguistic uncertainty* (notional confusion), *variability uncertainty* (e.g., meteorological conditions and natural elements), *knowledge uncertainty* (e.g., suppression effectiveness, response of natural resources to fires) as well as *decision uncertainty* (e.g., varying social preferences through time, agency interests and priorities conflicts) (Thompson and Calkin 2011).

## Concluding remarks

Our review shows the worldwide evolution of DSSs based on mathematical/economic algorithms or GIS capabilities. Most DSSs are constructed from similar basic subsystems that aim at gaining full understanding through data analysis and then making the best management decisions within a narrow time frame. This is challenging in natural disaster management where minimizing environmental, social and economic impacts is the overall goal.

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