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Review

Review of methods for modelling forest fire risk and hazard

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Forest fires (wildfires) have become a major concern for several environmental experts. Assessment of fire effects at local scale is increasingly considered a critical aspect of ecosystem functioning, since fire plays a crucial role in vegetation composition, biodiversity, soil erosion and the hydrological cycle. At global scale, fire is the most generalized means of transforming tropical forest in agricultural areas, and it has severe impacts on global atmospheric chemistry. Fire is a natural factor in many climates with high levels of vegetation stress. However, changes in traditional land use such as hunting, charcoal production, inefficient logging practices and rural abandonment patterns, which have been identified as major causes of wild fires, have recently modified the incidence of fire. Several assessment techniques and methods have been developed to help model and evaluate forest fire risk and hazard. There is the need to identify a method or combination of methods to help model forest fire risk and hazard to enable the sustainability of the natural resources. In this paper, the various methods are reviewed in order to enhance the use of appropriate method(s) for forest fire risk and hazard management. From the review and deductions of the methods, it was concluded that spatial multi-criteria modelling and evaluation (SMCME) of fire risk and hazard is preferred. It was also deduced that combination of SMCME with other methods has proven to be more efficient and effective when compared with the use of individual methods.

Key words: Forest fires, risk, hazard, management.

INTRODUCTION

Wildfires are inevitable companions of forests and foresters across the world and its spread revolves around four main factors: (i) the state and nature of the fuel, that is, proportion of live or dead vegetation, compactness, morphology, species, density, stratification and moisture content (ii) the physical environment, that is, weather conditions and topography (iii) causal factors (human-or natural-related) and (iv) means of prevention and suppression. Fire hazard is defined by both (i) and (ii) and has two types of variations: a spatial and long-term one, related to fuel types and topography and a temporal and short-term one, related to fuel moisture content and weather conditions. Fire risk accounts for (iii) and (iv) (Blanc et al., 1987; Chuvieco and Martin, 1994). Wildfires are considered as a serious

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problem that distresses many terrestrial ecosystems in the Earth system and causes economic damage to people such as missing income relative to the land use, destruction and loss of property, damages to agriculture, and loss of biodiversity. It is also one of the most important parts of land degradation that is caused by deforestation and desertification (Hernandez-Leal et al., 2006).

Stolle and Lambin (2003) noted that flammable fuel depends on climatic conditions, soil, vegetation and previous fire events. The ignition source is natural (for example lightening) or anthropogenic. If the ignition source is anthro-pogenic, it can be caused deliberately (as part of land management) or accidently through negligence. Preventing a small fraction of these fires would account for significant savings in the natural and human resources. Apart from preventive measures, early detection and suppression of fires is the only way to minimise the damage and casualties. Systems for early detection of forest fires have evolved over the past decades based on advances in related technologies. Wildfire is a paradox, it kills plants and animals and can cause wide-ranging damages to the ecosystem. On the other hand, it can be very beneficial in terms of nutrient recycling and forest regeneration. In some areas, natural wildfires have historically adapted with ecologically positive effects. Other ecosystems are susceptible to severe damages, causing a local extinction of species or considerable changes in ecosystem functions (e.g. soil, hydrology). Integrated modelling approaches could provide helpful insights into wildfire-environmental interactions. Globally, the majority of wildfires are caused by human activities in a direct or indirect form. An anthropogenic influenced wildfire regime (frequency, distribution) will potentially affect human activities. This inter-relationship between humans and wildfires has initiated many scientific studies.

Millington et al. (2008) and Schweitzer and Priess (2010) mentioned in their study (the presentation of an agent-based approach: Simulated land-use management influencing wildfire risk that only a few models exist which consider human activities and the interactions with vegetation-wildfire dynamics. In the paper, the authors presented preliminary results from a modelling approach which captures the wildfire behaviour in Northern Mongolia. The approach aimed at analysing impacts of wildfires on the socio-environment, including feedbacks related to carbon dynamics, biomass availability (in forests and grasslands) and the effects on land use. Therefore newly developed wildfire module on the basis of a well-established wildfire model linked to dynamic land-use model, which integrates new model capabilities of simulating wildfire spread and intensity would be appropriate.

Wildfires play an important role in terrestrial ecosystems, global biogeochemical cycles and climate. They are biological filter, regulator (Bowman et al., 2009; Jin, 2010) and global vegetation consumer (Bond and Keeley, 2005; Jin, 2010). Wildfires influence ecosystems directly by disturbing competition relations between and within species and by accelerating the carbon cycle, nutrient cycle, hydrological cycle and energy cycle (Thonicke et al., 2001; Jin, 2010). They also affect ecosystems indirectly by changing climate. Wildfires favour plants with distinct reproductive and survival strategies in different fire regimes.

Bowman et al. (2009), Bond and Keely (2005) and Jin (2010) argue that fire is another important determinant besides climate in shaping the global biomes distributions. Especially, wildfires have reduced the potential coverage of forest and facilitated the expansion of fire-dependent grassland and shrub land. Their simulations show that forest would at least double in extent in the absence of fire. Wildfires accelerate the natural carbon cycle of primary production and respiration. Regions that have long served as carbon sinks may suddenly become sources of carbon emission due to fires (van der Werf et al., 2004; Jin, 2010). There is, however, the need to detect wild fires and suppress them.

Fire detection and monitoring

Traditional ground-based visual detection methods are not always appropriate for offering reliable information on fire location, size and intensity due to the small field of view and often difficult terrain. Remote sensing has proven to be a valuable data source in different phases of fire management both before (prevention) and after the fire (damage assessment). Remote sensing observation has significant advantages over conventional fire detection and fire monitoring methods because of its repetitive and consistent coverage over large areas of land (Martin et al., 1999). Fire produces four forms of signal that are easily observed from space (Robinson, 1991; Martin et al., 1999). These are direct radiation from active fires (heat and light), smoke, post-fire char, and altered vegetative structure (scar). Fire detection from satellite images initially focused on analysing the first type of signal (Martin et al., 1999). There are a number of satellites and aircraft-borne remote sensing systems which can contribute to fire monitoring from space, including NOAA-AVHRR, Landsat- TM and MSS, SPOT, GOES, DMSP, ERS-ATSR, and JERS. The temporal, spectral and spatial characteristics of these instruments provide a wide range of sensing capabilities and some of them have been shown to be well adapted to fire detection application. NOAA-AVHRR and GOES have provided long-term operational systems, allowing low cost direct reception and near real-time fire information (Martin et al., 1999). The usefulness of operational near real-time fire detection from space is obviously very much dependent on observation frequency. Meteorological satellites are more appropriate because of their high repetition coverage. The geostationary GOES satellite series offer images every 30 min but only covers the American continents. The polar orbiting NOAA-AVHRR series acquire images over the same area every 12 h for the same satellite, but cover the entire world (Martin et al., 1999). Therefore, NOAA-AVHRR has been used most extensively for detecting and monitoring forest fires. Temporal resolution of AVHRR data may also be used to follow the spatial evolution of large fires, providing significant information for fire behaviour modelling. AVHRR images can provide valuable information because of the possibility of monitoring fire growth at least every 6 h (when using two NOAA satellites, morning and afternoon). Coarse spatial resolution of AVHRR data restrict this potential to large fires, whose size and duration are enough to be followed in time series of AVHRR image data (Martin et al., 1999).

The applications of GIS to fire risk modelling have considered a wide range of hazard variables, depending on the specific characteristics of fire events in the different test sites. Nevertheless it can be summarised into several important variables, such as topography (elevation, slope, aspect and illumination), vegetation (fuel type, moisture content), weather patterns (temperature, relative humidity, wind and precipitation), accessibility to roads and camping sites, land property type, distance to cities, soils, fire history and water availability.

Thus, this paper seeks to review the various methods that are being used to model and evaluate forest fire risk and hazard in order to enhance the appropriate adoption of method(s) for effective and efficient prevention, control and complete elimination of wildfires in the fragile ecosystem.

METHODS FOR FIRE RISK AND HAZARD MODELLING

To model and evaluate fire risk and hazard, there is the need for proper fire risk assessment. The following sections look at factors influencing fire behaviour, the risk assessment methods, modelling of fire risk and hazard methods.

Factors influencing fire behaviour

The factors influencing fire behaviour can either be natural or man-induced. Fire behaviour is a descriptive term used to designate what fire does and how it behaves. It estimates what a fire will do and relates to intensity, flame and rate of spread of specific fire. A product of environmental factors which interact with each other includes fuel, topography, weather and fire. The intensity and speed with which a fire travels depends on the amount and arrangement of the fine dead fuel, moisture content of the dead fuel, wind speed near the flaming zone, terrain and slope (Gould, 2005). The behaviour of a spreading fire is determined by factors such as weather, topography, fuel quantity and fuel moisture content. Countryman (1972) in Pyne et al. (1996) presented the concept of the fire environment- the surrounding conditions, influences, and modifying forces that determine the behaviour of a fire. Topography, fuel, weather and the fire itself are the interacting influences that make up the fire environment. This is illustrated as a fire environment triangle with the fire in the centre.

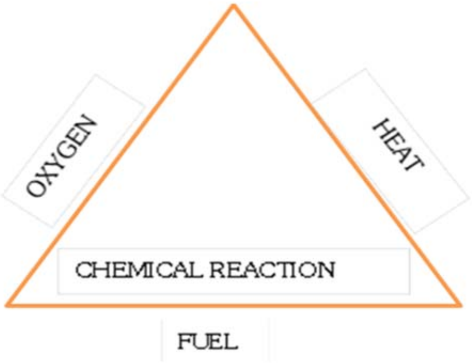

Figure 1. Fire triangle.

The changing states of each of the environmental components; fuel, topography and weather and their interaction with each other as well as the fire itself determine the characteristics and behaviour of a fire at any given moment. Changes in fire behaviour in space and time occur in relation to changes in the environmental components. From a wildland fire standpoint, topography does not vary with time, but can vary greatly in space. The fuel component varies in both space and time. Weather is the most variable component, changing rapidly in both space and time (Pyne et al., 1996). Figure 1 is the fire triangle. The fire triangle or combustion triangle is a simple model for understanding the necessary ingredients for most fires. The triangle illustrates the three elements a fire needs to ignite: heat, fuel and an oxidising agent (usually oxygen). A fire naturally occurs when the elements are present and combined in the right mixture. A fire can be prevented or extinguished by removing any one of the elements in the fire triangle.

Natural factors for fire ignition

The following are present details of some natural factors that contribute to fire ignition and propagation. The natural factors are topography, vegetation, fuel as well as weather.

Topography

Topography includes the elements of slope steepness, aspect, elevation and configuration of the land. Variations in topography can cause dramatic changes in fire behaviour as a fire progress over the terrain. Although topography may not change in time, it affects the way in which fuel and weather change. The fire environment triangle symbolises this interaction among the elements. Topography modifies general weather patterns, producing localised weather conditions that in turn affect fuel type and moisture content (Vadrevu et al., 2009; Pyne et al., 1996). For the past several years, fire behaviour models have incorporated the interaction of fire spread with fuels, weather and terrain (Vadrevu et al., 2009; Albini, 1976; Rothermel, 1983). The effect of terrain attributes on forest survival following wildfire has been assessed by Kushla and Ripple (1997) and others. Four different topographic parameters explained below, as causative factors of fires were elevation, slope, aspect, and a compound topographic index (Vadrevu et al., 2009).

Elevation

Elevation is considered as an influencing factor of forest fire, because elevation relates to precipitation and temperature. In general, with the increasing of elevation, precipitation usually increases. Therefore, the probability of fire is less in areas of higher elevation. In some specific situations however, precipitation does not follow this rule. A similar use of elevation factor for forest fire estimation is performed by Chuvieco and Congalton (1989). For temperature, higher elevation leads to lower temperature, which also means there will be lower probability for fire to appear in higher elevation area. Both precipitation and temperature are influenced by elevation and the effects on the forest fire are the same, so they can be considered together.

Elevation above sea level influences general climate and thereby affects fuel availability. Length of fire season and fuel vary with elevation due to differences in amount of precipitation received, snow melt dates, green up and curing dates (Pyne et al., 1996). Elevation is an important physiographic factor that is related to wind behaviour and hence affects fire proneness (Rothermel, 1983). Fire travels most rapidly up-slope and least rapidly down-slope.

Aspect

Aspect is the direction a slope is facing. Aspect affects fire behaviour through variations in the amount of solar radiation and wind that different aspects receive. Generally, in the northern hemisphere, south and southwest aspects are most favourable for fire to start and spread (Pyne et al., 1996). These aspects receive more sunshine and therefore have lower humidity and higher fuel temperatures (Pyne et al., 1996). Solar radiation intensity is greatest when the slope is perpendicular to the sun angle. In the northern hemisphere, fuels on slopes with an easterly aspect will dry out earlier in the day, but may not become as dry as those on slopes with a westerly aspect (Pyne et al., 1996). It can be deduced that the slope which faces the wind direction is easier to cause raging fire. A north-facing slope also receives less sunlight than a south facing slope. Thus, Southern aspects receive more direct heat from the sun, drying both the soil and the vegetation.

Slope

Slope is an extremely important factor among topographic factors. Slope has a large effect on the speed of fire when it is spreading. Kushla and Ripple (1997), mention that fire always spreads faster up-slope than down-slope. Slope steepness also affects the radiation intensity and fuel moisture. The slopes where the fuel will be the driest vary with time of year, time of day, and latitude. Thus, as a fire moves over the landscape its behaviour can be expected to change with time of day and topographic characteristics because of the variations brought about by the different amounts and intensity of the solar radiation received (Pyne et al., 1996). Slope significantly influences the forward rate of spread of surface fires by modifying the degree of preheating of the unburnt fuel immediately in front of the flames. In a head fire, this is achieved, as with wind; by changing the flames to a very acute angle and with slopes exceeding 15 - 20°C, the flame propagation process involves almost continuous flame contact (Trollope et al., 2002). Conversely a down slope decreases the rate of spread of surface head fires (Trollope et al., 2002). Steep slopes increase the speed of fire a lot, because convective preheating and ignition rate are more effective. In other words, larger slope of the terrain will lead to larger probability of causing fire.

Vegetation and fuel

Vegetation type has a strong relationship with the forest fire risk. Different types of vegetation have different kinds of combustibility. Generally, coniferous forest has a higher probability for fire risk than deciduous forest, because coniferous trees contain less water and higher oiliness (Li, 1998).

Fuel is a critical leg in both of the fire triangles: fuel, oxygen, and heat of the fire fundamental triangle; as well as fuel, topography and weather of the fire environment triangle. Fuel does not cause fire, but it certainly changes the character of a fire, affecting the ease of ignition as well as fire size and intensity (Pyne et al., 1996). Fuel can be described in terms of both fuel state and fuel type.

Fuel state refers to the moisture content of the fuel and whether it is alive or dead. Fuel type is a description of the fuel itself. The description of fuel type includes physical properties of fuel, fuel component and fuel complexes. Fuel properties that affect the way the material burns include quantity, size, compactness and arrangement. Fuel components, which are related to the way vegetation grows may be specified as ground, surface and crown fuel as well as grass, litter, brush, or over story. Fuel complexes, which are associations of components include grass and timber with grass and litter understory (Pyne et al., 1996). Moisture content, expressed as a fraction, is the mass of water held by unit mass of oven dry fuel and is determined primarily by fuel type and weather. It may also be expressed as a percentage of the fuel oven dry weight. Fuel moisture is normally expressed on a dry matter basis and is a critical factor in determining the intensity of a fire because it affects the ease of ignition, the quantity of fuel consumed and the combustion rate of the different types of fuel. The most important influence of fuel moisture on fire behaviour is the smothering effect of the water vapour released from the burning fuel. It reduces the amount of oxygen in the immediate proximity of the burning plant material thus decreasing the rate of combustion. Fuel load is regarded as one of the most important factors influencing fire behaviour because the total amount of heat energy available for release during a fire is related to the quantity of fuel. Assuming a constant heat yield, the intensity of a fire is directly proportional to the amount of fuel available for combustion at any given rate of spread of the fire front.

Weather

Forest fires are strongly linked to weather and climate (Flannigan and Wotton, 2001). Weather is one of the most important factors affecting the behaviour of a fire. The most important components of weather affecting the behaviour of a fire are air temperature, relative humidity and wind speed.

Air temperature plays an important role in fire behaviour. Its direct effect is to influence the temperature of the fuel and therefore the quantity of heat energy required to raise it to its ignition point. Air temperature also has indirect effects via its influence on the relative humidity of the atmosphere and moisture losses by evaporation. Research in South Africa indicated that air temperature had a highly significant positive effect on the intensity of fires in African grasslands and savannas. The relative humidity of the atmosphere influences the moisture content of the fuel when it is fully cured.

It is positively correlated with fuel moisture and therefore plays an important role in controlling the flammability of fine fuels. The combustion rate of a fire is positively influenced by the rate of oxygen supply to the fire (Brown and Davis, 1973; Trollope et al., 2002) hence the effect of wind speed on fire behaviour. Wind also causes the angle of the flames to become more acute. With increased wind velocities, the flames are forced into the unburned material ahead of the fire front resulting in more efficient preheating of the fuel and greater rates of spread in surface head fires (Luke and McArthur, 1978; Cheney, 1981; Trollope et al., 2002). It was stated that increased wind speeds cause greater rates of spread and therefore more intense fires (Brown and Davis, 1973; Luke and McArthur, 1978; Trollope et al., 2002). However, flame height does not necessarily increase with increased wind speeds because these cause the flames to assume a more acute angle and this may prevent the ignition of aerial fuels.

Human factors for fire ignition

There is no fire without a cause. The factors necessary for fires to occur are presence of flammable fuel and an ignition source. The ignition source of fires can be natural causes (for example lightening) or human causes (anthropogenic) (Stolle and Lambin, 2003). In general, natural causes do not seem to be of great interest for the wildfire research community. Most of the fires are caused by human activities and that is where most of the research emphasis is laid on (Stolle and Lambin, 2003). Forest fires, for example, in Ghana are usually human-induced. Human causes of fire can be categorised as direct cause of setting up fires as a method or tool for land clearing (Tomich et al., 1998; Applegate et al., 2001; Santoso, 2006), traditional beliefs and indirect cause of fire by human activities that favour the occurrences and potentially increase the risk of fires such as logging, road development, resettlement, etc. (Santoso, 2006). In the Indonesian context, development can be often equated to opening access to large tracts of sparsely populated forest land for other uses (Bowen et al., 2000). Initially, primary forests are humid, have a closed canopy with little undergrowth and have a low fire risk. However, where roads penetrate primary forest to aid logging, humidity become lower, wind speeds increase, and there is always a ready supply of drier fuel available, therefore the risk to fire is considerably increased (Nicolas and Beebe, 1999). The agro-industrial crop arrives and takes over the area once the forests have been logged. Ideally the new estate crop is established at the start of the next rainy season to allow it to gain a rapid control of the site and suppress weed growth. But often far greater areas are cleared at one time than planted. In either case, the open ground encourages the rapid colonization by herbs. The area then becomes highly vulnerable to repeat fires in the next dry period (Bowen et al., 2000).

In most parts of Africa, the environment is undergoing rapid desertification due to rampant bush burning for farming and hunting. The effects of these activities on the ecosystem cannot be overemphasised. Bush burning activities generally continue to reduce the flora and fauna around the globe to levels that are destructive to biological diversity. The principal elements of the environment such as vegetation and water have been severely impacted. This has significant implication for farmers' income and food security of the family. It is therefore imperative to consider the risks involved in such bush burning.

Risk assessment

Fire risk assessment should be seen as a specific part of a wider, overall, assessment of the risk to which the ecosystem is exposed and may be part of an overall program of risk reduction. There are three parts to fire risk assessment:

Initial assessment

This involves the identification of the hazards and sizing the risks. After identification of the hazard, one important thing is to decide whether the hazard from fire is important enough to be a source of serious potential harm or in any given situation may cause loss, death, injury or damage. Consideration is made on how likely it is that each hazard could cause harm. This will determine whether or not there is the need to do more to reduce the risk. Even after all precautions have been taken, some risk usually remains. A decision is made for each significant hazard whether the remaining risk requires any control measures.

Risk reduction

Having made the initial assessment there follows the important task of reducing the hazards and risks. It will almost certainly be the case that some reductions may be effected immediately, and these short-term measures would include such things as improving the environmental practices- the management of waste and rubbish, and the implementation of a programme of fire safety training for employees and community members. Other long-term measures would include such things as the installation of a fire suppression system, the change in some negative beliefs and the substitution of hazardous processes and materials with less hazardous ones.

Final risk assessment

When the hazards and risks have been reduced to what, at the time, appears to be an irreducible level, there follows a more rigorous final assessment of the risk. The final assessment will determine the risk categorisation which conventionally will be defined as high, normal or low. Of course in larger premises such as a forest, it will be quite normal to have different risk categories for different parts of the area. The final assessment will have three outcomes: it will determine whether the areas, or parts of it, are to be categorised as being of high, normal, or low risk; this in turn will determine the fire precautionary measures required in the area, and it will be the starting point in the formulation of an emergency plan. In carrying out the risk assessment it will be necessary to have in mind but not limited to the following factors: the living things present in the area, the use to which the area is put, the sources of ignition present, the use of flammable materials, the contents of the area, the structural features of the area, traditional beliefs of the people in the area and fire education level in the area. It is worth mentioning that precautionary measures of people are directly connected to their risk perceptions (Rosenstock et al., 1988). For example; people who expect higher probability of being hurt by fire will tend to take more precautionary measures. Previous studies as captured in Shavit et al. (2013): “The Effect of Fire on Emotions and Risk perception: A field study after the Carmel Forest Fire Disaster” clearly showed factors affecting individuals’ risk perception of being hurt by fire.

In large or complex forest area it may simplify the task, and indeed be more appropriate, if all three parts of the exercise are carried out by treating distinct areas such as forest, communities, and water bodies as separate entities.

Risk assessment techniques provide a valuable tool in attempting to categorise the degree and severity of risk to which an organisation, nation or the ecosystem might be liable. While no method is infallible, sensible use of risk assessment and application of the lessons drawn can result in more cost effective introduction of fire protective measures.

Risk assessment methods

There is no single ‘correct’ way of carrying out risk assessment, there are three methods which might be useful, each of which makes clear what is to be understood by the terms high, normal and low risk. These are:

1. The risk category indicator method: This is a diagnostic method in which the various elements in the area are classified in such a way as to indicate the area in which they are found and should be categorised as being high, normal, or low risk. Elements which may give rise to high risk indicators in the case of forest include: communities; vegetation; wind; topography; road network; and negative traditional beliefs.
2. The risk value matrix method: Unlike the Risk Category Indicator method, this method attempts to put the risk assessment onto a quantitative basis. However, it cannot be strongly stressed that the numbers involved are purely relative, and therefore they have no absolute significance whatsoever. Whilst all risks are made up of two elements- the probability that an event will occur and the consequences of that occurrence, the relative contributions of these two elements to risk may vary considerably. Formula for risk value: Remembering that the two elements of risk are the fire hazard and the fire risk, the risk value is defined by the simple formula:

Risk value = fire hazard value x fire risk value

If the size of the fire hazard and the fire risk is expressed by assigning values to them then, by applying the formula, a number obtain would be a measure of the risk value. The size of the risk value then becomes the basis for categorising the area as being of high, normal or low risk.

Quantifying the fire hazard and the fire risk

This is easily done by: classifying the fire hazards;

Table 1. Classifications of fire risk and hazard.

Fire hazard (description)	Value	Fire risk (description)
Negligible	1	Unlikely
Slight	2	Possible
Moderate	3	Quite possible
Severe	4	Likely
Very Severe	5	Very likely

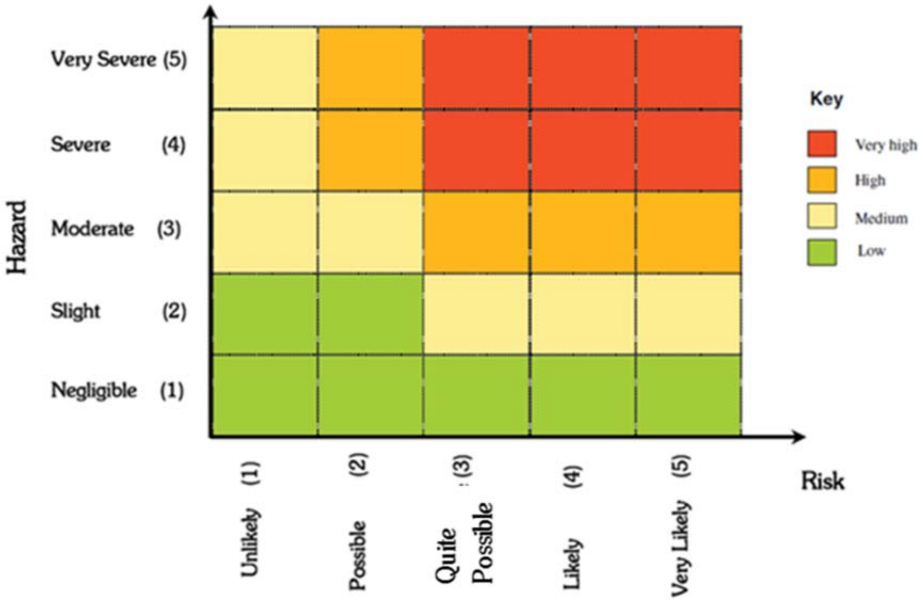

Figure 2. Risk rating matrix (Anon., 2011).

describing them as being between negligible and very severe; and assigning a numerical value to each description. Similarly, it may classify the fire risks by describing them as being between unlikely to very likely, and by assigning a numerical value to each of these descriptions. Table 1 is a classification of fire risk and hazard.

Using the risk value formula for all possible combinations of fire hazard values and fire risk values, a set of twenty five numbers are obtained. The risk values obtained can then be displayed as a two dimensional grid (risk value matrix). Figure 2 shows a risk rating matrix (Anon., 2011). The final task in this method is to decide the ranges of the risk values that will correspond to our three categories of risk. 3. The algorithmic method: An algorithm is a two dimensional diagrammatic representation of the steps to be undertaken in order to make a decision, solve a problem, or carry out a process. In short, it is a flowchart.

METHODS FOR FOREST FIRE RISK MODELLING

Forest fire risk assessment is very important for fire management. It may be considered at different spatial and temporal resolutions: global and local; short term, and long-term fire risk estimation. Global scales can contribute to the establishment of general guidelines for fire management at continental level, while local scales are adapted to specific fire prevention resources of small regions (Chuvieco et al., 1999). Risk should, however, be estimated in order to plan for the necessary resources for fire management.

Short-term fire risk estimation

Short-term estimation of risk is required to take update decisions on fire pre-suppression and suppression activities, which should ideally provide daily estimations of fire risk and it is commonly based on weather data; however, recently satellite information is also being considered (Chuvieco et al., 1999).

The physical basis to estimate fire risk has many similarities in the different ecosystems, the actual formulation varies from one country to another, and therefore a great diversity of indices is available since many of them have been developed primarily for specific geographic area (Marzano et al., 2005). Long term estimation, however, is necessary.

Long-term fire risk estimation

Long-term estimation addresses the general, more permanent, planning of fire fighting resources, which is related to the more structural factors that affect fire ignition or fire propagation, such as topography or terrain characteristics, vegetation structure, human activities or weather patterns. These factors can be considered stable at least during a whole fire season; therefore they do not need to be updated frequently.

Two to five year updates are accurate enough for fire management (Chuvieco et al., 1999). There are some common methods used in long-term fire risk estimation, such as qualitative methods, quantitative methods based on expert knowledge (multi-criteria evaluation techniques), regression techniques (linear regression and logistic regression), and artificial neural networks (Chuvieco et al., 1999; Marzano et al., 2005).

Logistic regression model

One quantitative approach to obtain a fire risk index is to calculate the weights of the different variables using regression analysis techniques such as logistic regression. In the context of fire risk assessment, fire occurrence (usually expressed as number of ignition points/areas or as a proportion of burned area) is the dependent variable, while fire danger variables (slope, fuels, fuel moisture, road network, recreational areas, etc.) are the independent ones. Coefficients of regression become the weights of each danger variable to produce the synthetic fire risk map (Marzano et al., 2005).

Logistic regression is a quite flexible tool, since it accepts the input of a dataset composed of continuous and/or categorical variables as well as non-normally distributed one. Several independent variables can be included in the model. Its main characteristic refers to the binary format of the dependent variable (Chuvieco et al., 1999). Thoha (2006) applied logistic regression on forest fire prediction in peatland areas in Bengkalis, Riau Province.

Multi-criteria evaluation

Multi-criteria evaluation (MCE) is a decision making tool developed for complex multi-criteria problems that include qualitative and/or quantitative aspects of the problem in the decision-making process (Mendoza et al., 1999). The MCE techniques (Chuvieco et al., 1999) may be a good alternative to reduce the subjectivity of this assigning process, since the opinion of experts may be quantitatively assessed. Moreover, each expert's opinion may be weighted according to his/her degree of knowledge in the field of study. The MCE techniques have been used for fire danger mapping, weighting each danger variable after the expert's opinion in two different scenarios (Chuvieco et al., 1999). Multi-criteria analysis can be implemented using analytical hierarchy process (AHP) (Saaty, 1980). The AHP method approaches decision-making by arranging the important components of a problem into a hierarchical structure similar to a family tree. The AHP method reduces complex decisions into a series of simple comparisons, called pairwise comparisons, between elements of the decision hierarchy. By synthesising the results of these comparisons, AHP can provide the best decision and provide a clear rationale for the choice (Mendoza et al., 1999).

Power (2006), stated that "Spatial decision support systems (SDSS) provide a powerful and easy interface to combine cartographic models and other image data to define solutions to unstructured and semi-structured problems. SDSS supports a range of decision-making styles and approaches by generating a series of feasible alternatives through an interactive and recursive process in which decision making proceeds by multiple passes, sometimes involving alternative routes rather than a simple linear path. Examples where SDSS techniques have been used in fire management include Varela et al. (2005), Barrett et al. (1999) and Jones et al. (2004). The basic strategy is to divide the problem into well-defined smaller pieces, analyse each piece separately, and then integrate the pieces logically to produce a solution, following Jankowski's (1995) general framework. Decision criteria are formally evaluated and allocated a score based carry within the decision making process. In many instances this process is achieved using multi-criteria evaluation (MCE). The criteria considered in definition of potential fire hazard are slope, aspect, vegetation and communities".

A comprehensive consideration for fire risk implies taking into account a wide range of variables. A common terminology distinguishes between the concepts of risk associated with the beginning of a fire (fire ignition risk or flammability) and to the spreading of an active fire (fire behaviour risk or fire hazard). In each case, different variables and different risk weights should be considered. However, both approaches require being capable of integrating different spatial variables. GIS provides tools to on expert opinion regarding the weight each criteria will create, transform and combine geo-referenced variables. Therefore, GIS can spatially integrate several hazard variables related to fire risk and provide tools for risk analysis (Chuvieco et al., 1999). The applications of GIS to fire risk modelling have considered a wide range of hazard variables, depending on the specific characteristics of fire events in the different test sites.

Integrated spatial multi-criteria methods for fire risk and hazard modelling

The integrated approach makes extensive use of spatial and non-spatial data for modelling fire risk and hazard.

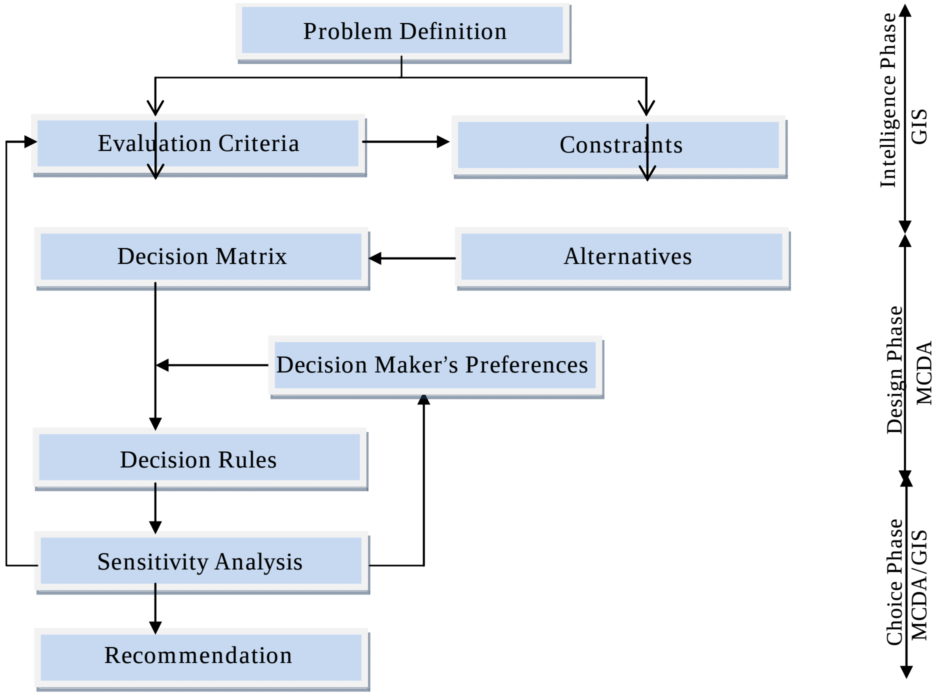

Figure 3. Framework for spatial multi-criteria decision analysis (Malczewski, 1999).

This method combines two or more methods to help in decision analysis of optimal model for fire risk and hazard.

Decision analysis is a set of systematic procedures for analysing complex decision problems. These procedures include dividing the decision problems into smaller and more understandable parts; analysing each part, and integrating the parts in a logical manner to produce a meaningful solution (Figure 3) (Malczewski, 1997). In general, multi-criteria decision analysis (MCDA) problems involve six components (Keeney and Raiffa, 1976; Pitz and McKillip, 1984). These components are as follows:

1. A goal or a set of goals the decision maker wants to achieve;
2. The decision maker or a group of decision makers involved in the decision making process with their preferences with respect to the evaluation criteria;
3. A set of evaluation criteria (objectives and/or physical attributes);
4. The set of decision alternatives;
5. The set of uncontrollable variables or states of nature (decision environment); and
6. The set of outcomes or consequences associated with each alternative attribute pair.

MCDA techniques can be used to identify a single most preferred option, to rank options, to list a limited number of options for subsequent detailed evaluation, or to distinguish acceptable from unacceptable possibilities. There are many MCDA approaches which differ in how they combine and utilise the data. MCDA approaches can be classified on the basis of the major components of multi-criteria decision analysis. Three different classifications can be made. These are:

1. Multi-objective decision making (MODM) versus multi-attribute decision making (MADM);
2. Individual versus group decision maker problems; and
3. Decisions under certainty versus decisions under uncertainty.

The distinction between MADM and MODM is based on the evaluation criteria which are the standards of judgments or rules on which the alternatives are ranked according to their desirability. Criterion is a general term and includes both the concepts of attributes and objectives. An attribute is a measurable quantity whose value reflects the degree to which a particular objective is achieved. An objective is a statement about the desired state of the system under consideration (Chankong and Haimes, 1983). It indicates the directions of improvement of one or more attributes. Objectives are functionality related, or derived from a set of attributes (Malczewski, 1999). There might be formal relationship between objectives and attributes, but usually the relationship is informal. To assign an attribute to a given objective, two properties, which are comprehendsiveness and measurability, should be satisfied. An attribute is comprehensive if its value sufficiently indicates the degree to which the objective is met. And it is measurable if it is reasonably practical to assign a value in a relevant measurement scale. The ratio, interval, ordinal and binary scales are suitable for measuring attributes, whereas nominal scale is not since it does not allow an ordering of the alternatives (Janssen, 1992). MADM problems require that choices be made among alternatives described by their attributes. The set of attributes is given explicitly and multi-attribute problems have a finite set of feasible alternatives. Unlike MADM, MODM problems require that means-ends relationships be specified, since they deal explicitly with the relationship of attributes of alternatives to higher level objectives. MODM involves designing the alternatives and searching for the best decisions among an infinite or very large set of feasible alternatives. Each alternative is defined implicitly in terms of the decision variables and evaluated by means of objective functions (Malczewski, 1997).

Both MADM and MODM problems can be further classified as individual and group decision making depending on the goal-preference structure. If there is a single goal preference, the problem, is considered as individual decision-making regardless of the number of decision makers involved in the process. However, if the individual or interest groups are characterized by different goal preferences, the problem becomes the group decision making (Malczewski, 1997).

The other classification depends on the certainty of the decision. If the decision maker has perfect knowledge of the decision environment and the amount of knowledge available is enough, then the decision is considered as decision under certainty. However, most of the real world decisions involve some aspects that are unknown and difficult to predict. This type of decisions is referred to as decisions under uncertainty. The decisions under uncertainty can be further subdivided into fuzzy and probabilistic decision making (Eastman et al., 1993). The probabilistic decisions are handled by probability theory and statistics; and the outcome of a stochastic event is either true or false. However, if the situation is ambiguous, the problem is structured as the degree of how much an event belongs to a class. This type of problems is handled by fuzzy set theory (Zadeh, 1965).

CONCLUSION

The use of GIS and RS technologies has improved tremen-dously for the collection, availability of data, and integrated management of spatial and non-spatial data for forest fire risk and hazard management.

The fire risk and hazard model generated from individual methods lacks the one stop solution for forest fire management. Hence, the need for the adoption of an integrated spatial multi-criteria approaches to fire risk and hazard modelling and evaluation.

Conflict of interests

The authors declare there is no conflict of interest.

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