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Management of Forest Fire Disaster: Perspectives from Swaziland

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1. INTRODUCTION

Forest fires (also known as 'wildfires') are extremely powerful and destructive phenomena which occur with significant frequency and intensity on many parts of the Earth. These fires are part of the Earth system and are an important ecosystem disturbance with varying return frequencies, resulting in landscape alteration and change as well as atmospheric changes on multiple time scales (Chuvieco and Kasischke, 2007). Fire is believed to be an ecological imperative in many of the indigenous, fire prone ecosystems of the world. These indigenous vegetation species are regarded as being fire adapted and dependant upon fire for their survival. Under normal circumstances, fire is therefore regarded as vital in maintaining the delicate balance of hundreds of millions of hectares of tropical and subtropical savannas and open forests, as well as coniferous forests of the temperate and the northern boreal zones that are quite well adapted to natural and even human-influenced fire regimes (Bond and Keeley, 2005). These ecosystems can, however, become more prone to forest fires due to invasive plant infestations, and human activities thus leading to substantial losses of bio-diversity (FAO, 2007). Such fires become a risk when their frequency or intensity destroys forests or vegetation beyond what is naturally admitted and threaten humans and their activities. Goldammer (2007) identifies several global issues and trends that are impacting the occurrence and consequences of forest fires on the environment and societies, and these include demographic changes, widespread poverty associated with unemployment, exurban migrations and land tenure conflicts, land-use change, expansion of the wildland-urban interface, climate change, and threats to human health, security and peace.

The socio-economic changes of our society have increased forest fire risk as experienced during the latter part of 20th century and first decade of the 21st century. Over this period, many regions of the world have and continue to experience a growing trend of excessive fire application in the forestry-agriculture interface, land-use systems and land-use change, and an increasing occurrence of extremely severe wildfires or 'megafires' (Goldammer, 2007). Due to the lack of consistent and coherent data on the statistics on the global occurrence and impact of forest fires, it is not possible to precisely determine the trend in the global number of such fires or the area burnt over long periods of time. However, evidence exists which indicates that there is an increase in the number of larger and more destructive fires (FAO, 2007). The high socio-economic and demographic changes experienced by many countries in many regions over the past few decades have been based in part upon the exploitation of natural resources and development of agro-based industries, both of which involve conversion of forests and intensification of land-uses (Murdiyarso et al., 2004). These wildfires cause widespread destruction and damage affecting economic sustainability and productivity for entire regions or countries. Recently, such fires have had an immense impact in areas such as Southern (Mediterranean) Europe, Southern and Eastern Africa, Australia, Southeast Asia, and Central and Northern Latin America. Using daily global observations from the Advanced Very

High Resolution Radiometers (AVHRR) on the series of National Oceanic and Atmospheric Administration (NOAA) meteorological satellites between 1982 and 1999, Carmona-Moreno et al. (2005) found that these regions always have a maximum of fire occurrence probability in a given trimester of the year and considered these as fire-prone areas-ecosystems. Similar patterns have also been confirmed by Chuvieco et al. (2008). The global distribution of fires detected by the MODIS sensor between January 2000 and December 2008 is shown in Fig. 1.

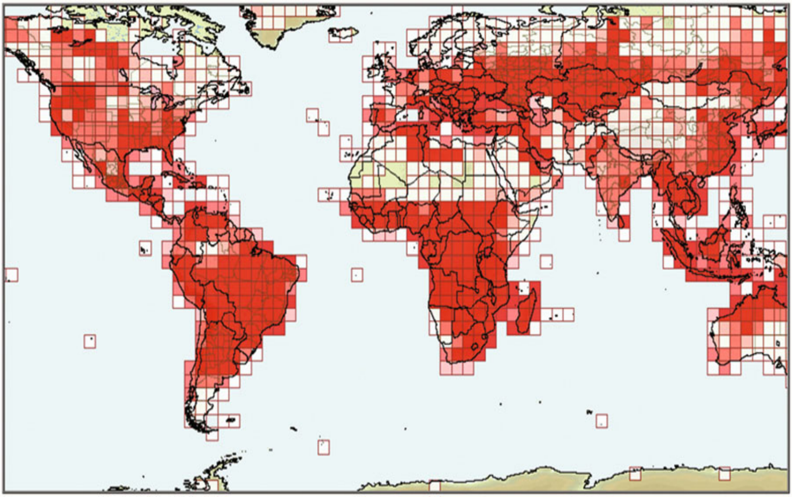

Fig. 1 Global active fire detections from MODIS for January 2000 to December 2008; dark red color in the figure indicates the highest number of fires detected (NASA/University of Maryland, 2002).

Historically, there have been some major forest fire disasters, which had considerable impacts on people and properties. Such include the October 1994 and October/November 1997 forest fires in Indonesia which affected around three million people and killed two hundred people, respectively (EM-DAT, 2008). The 1997 fires resulted in a haze that spread as far as the Philippines to the north, Sri Lanka to the west, and northern Australia to the south and an estimated 750,000 ha was affected. In 2007, forest fire killed more than 50 people in Greece. The forest fire records since the beginning of the twentieth century show many catastrophic forest fires affecting a large number of human populations all over the world. Table 1 shows the world's greatest forest fire disasters in terms of people killed. Sub-Saharan Africa is of exceptional note in this regard. Estimates show that about 17% of sub-equatorial Africa burns annually, accounting for 37% of the dry matter burned globally (Scholes et al., 1996); hence the African continent is often referred to as the "*Fire Continent*" (Pyne et al., 2004) followed at some distance by Australasia. The 2007 and 2008 fire seasons produced ravaging fires which uncharacteristically occurred in South Africa, Mozambique, Botswana and Swaziland.

This chapter highlights forest fire disasters and discusses forest fire management issues with a focus on the experiences from the kingdom of Swaziland. The role of remote sensing and geospatial technologies in the forest fire monitoring and management, possible early warning and mitigation of forest fires are also discussed.

Table 1. The ten most catastrophic forest fires in terms of people killed during 1980-2008 (EM-DAT, 2008)

Name of country	*Year of fire occurrence*	*No. of people killed*
Indonesia	1997	240
China	1987	191
Australia	1983	75
Greece	2007	67
Indonesia	1991	57
Nepal	1992	56
Mexico	1998	50
Mozambique	2008	49
Sudan	1998	47
Poland	1992	35

2. FOREST FIRE MONITORING TECHNIQUES

Long-term forest fire statistics are an indispensable instrument for forest management, emergency services planning, fire-fighting facilities and preventive measures. Hence, data and methods are required to integrate data from multiple sources and provide timely information for assessments of fire risk and probability (Chuvieco and Kasischke, 2007). However, as already alluded to, the lack of such data in many, particularly developing, countries inhibits the effective forest fire management. This therefore requires the consideration of sound alternatives that can derive critical information for fire scientists and decision makers.

Since the emergence of space technology in the 1960s, space-borne sensors now monitor the Earth continuously. Due to the large spatial and temporal variability in fire activity, satellite data provide the most useful means and the only practical way to monitor fire activity from a local to a global scale. There exist polar-orbiting and geostationary systems with full operational status and experimental systems providing systematic observations that have been used for the creation of long-term data fire mapping. In addition to providing fire data for use in long-term studies, these sensors provide synoptic snapshots of fire activity in near-real time to support operational fire management (Qu et al., 2008). Two general approaches are commonly used to monitor forest fires or biomass burning: post-fire burned areas mapping and active fires detection (Eva and Lambin, 1998). Post-fire burn detection is mostly done through measuring changes in surface reflectance before and after the fire mainly from red (0.65–0.70 μm) and near infrared (0.7–3.0 μm) information. This is based on the observation that burnt areas have a lower reflectance in the red and near infrared portions of the electromagnetic spectrum than healthy vegetation (Flannigan and Vonder Haar, 1986). In contrast, active fire detection by remote sensing systems is usually based on the detection of hot temperatures above normal environmental temperatures (threshold methods) and with respect to the background (contextual methods) and the detection of smoke plumes produced by fire emissions (San-Miguel-Ayanz et al., 2005). This is because the high temperature of fire enables the emission of thermal radiation with a peak in the middle infrared region, in accordance with Planck's theory of blackbody radiation. Therefore, active fire sensing is often done using middle infrared and also thermal infrared (usually around 3.7–11 μm) information from satellites (Dozier, 1981).

To date, a number of large-scale, multi-year fire datasets have been produced using observations acquired by various satellite-based sensors. Major long-term global records of active fires that have been generated include the Along Track Scanning Radiometer (ATSR) World Fire Atlas by the European

Space Agency (ESA) and the Advanced Very High Resolution Radiometer (AVHRR), Tropical Rainfall Measuring Mission's Visible and Infrared Scanner (TRMM VIRS) and Moderate Resolution Imaging Spectrometer (MODIS) by NASA. Geostationary fire monitoring has been undertaken using the GOES (WF-ABBA) and MSG SEVIRI (EUMETSAT Active Fire Monitoring) instruments. A number of these and other fire products are accessible through Web-based distribution systems, ranging from simple file distribution systems to complex visualization and search utilities using web GIS. Future systems are at advanced design stages and these include the NPP/NPOESS Visible Infrared Imagery Radiometer Suite (VIIRS) and sensors onboard the Global Monitoring for Environment and Security (GMES) Sentinel satellites and the provision of baseline high resolution fire observations for product validation should ensure the continuity of fire mapping and detection capabilities. The use of remote sensing for monitoring the distribution, frequency and impacts of wildfires is, therefore, a maturing scientific field which is gaining widespread applications in various countries of the world (Chuvieco and Kasischke, 2007).

3. CAUSES OF FOREST FIRE

It is basic scientific knowledge that for fire to occur, three elements are necessary for combustion, namely heat, oxygen and fuel and, in addition, the triangle of primary conditions that can affect extreme wildfire behavior consists of topography, fuels, and weather (Trollope et al., 2004). Hot, dry, and windy conditions are generally ideal for the rapid growth and spread of wildfires. Steeper slopes tend to increase the rate of fire spread. However, the determination of the causes of fires is an important undertaking that is necessary for the formulation of appropriate forest fire policies and management strategies.

It has been generally accepted and repeatedly quoted by bureaucrats that fires were caused by the El Nino Southern Oscillation (ENSO), and therefore, a natural disaster, which could not be prevented. However, a majority of fires are caused by people and most are lit deliberately to take advantage of the dry conditions to prepare land (or, as a tool in conflicts). Cyclical climate changes such as ENSO, similar to heat waves and droughts may increase the risk of these fire by providing the climatic conditions suitable for large forest fire episodes, such as the July 2007 Swaziland fire disaster (Dlamini, 2007), but it is hardly the underlying driver or cause. Recently, some researchers suggest the influence of solar activity as a possible cause of large forest fires (e.g., Gomesa and Radovanovic, 2008). In order to understand the topic fully, an appreciation of the difference in the characteristics of a "*natural fire*" and "*anthropogenic fire*" (i.e., fire originating from human intervention) is necessary. *Natural fires* typically occur seasonally and from a species diversity perspective and the more random the fire regime (vegetation age, time of year, weather, etc.), the more likely the fire is to actually maintain the biodiversity or indigenous flora and fauna of that area. These are commonly ignited by lightning in many African and other regions, but earthquakes, volcanoes and landslides are also known to start forest fires (Trollope et al., 2004).

Anthropogenic fires, on the other hand, result from the intervention of humans and purposeful or accidental ignitions are becoming increasingly frequent, leading to land degradation and loss of biodiversity. It is these types of wildfire which are the most damaging and which sow widespread destruction throughout southern Africa. These anthropogenic or unnatural fires can be split into unwanted, unmanaged wildfires and managed, or prescribed fires, which can be beneficial, provided these are implemented by experienced burners under carefully controlled conditions. The unmanaged fires are ignited through arson and accidents from sources such as cigarettes, matches and powerline sparks. The rains in the summer rainfall region, whilst late, are concentrated, leading to extraordinary growth of vegetation. In turn, this will lead to increased biomass or higher fire fuel loads. If these fuel loads are not reduced and there is a protracted dry season, extreme fire danger conditions will prevail. Over the winter rainfall area prevailing dry conditions coupled with high temperatures seem set to continue. Fuel loads can be very high, depending upon age of forest and seasonal rainfall. It is estimated that more approximately 40 to 95% of forest fires are caused by human intervention exceptions being the boreal regions of North America and Russia where lightning is the major cause (Tishkov, 2004; FAO, 2007). Based on domain knowledge, the key characteristic differences between natural and anthropogenic fires can be summarized as shown in Table 2.

Table 2. Key characteristics of natural and anthropogenic fires

Natural fires	*Anthropogenic fires*
The primary source of ignition is lightning.	The primary source of ignition is usually human intervention.
Due to the source of ignition, occurrence is most frequent during the rainy seasons.	Due to the source of ignition, frequency is usually higher and mostly occurring in the dry season (often protracted by late rains).
Typically high moisture content of the vegetation and accompanying rain contains fire to smaller patches.	High fire load due to the low moisture content of the vegetation results in large patches being burnt.
Indigenous vegetation is fire adapted and dependant on fire for biodiversity.	Radical fire spread through invasive alien plants, often with high resin or oil content.
A lower fire intensity and spread occurs in normal circumstances.	A high fire intensity (hot fire) and spread rate.

4. AN OVERVIEW OF SWAZILAND

The Kingdom of Swaziland, located in southern Africa, is 17,364 km^2 in extent straddling latitudes 25°40′ and 27°20′ South and longitudes 30°40′ and 32°10′ East (Fig. 2). The country is sandwiched between South Africa to the north, west and south, and Mozambique to the east. It is also endowed with tremendous natural diversity and complex terrain with elevation that decreases from an average of 1400 m above mean sea level on the west to below 100 m on the eastern part of the country resulting in four major eco-climatic regions (see Fig. 2), namely the Highveld, Middleveld, Lowveld and the Lubombo Plateau (Goudie and Price-Williams, 1983). Climatic variations within the country are largely controlled by the topography and there are four seasons within a year with December being mid-summer and June mid-winter. Mean annual rainfall also varies extensively from above 2000 mm per annum in the Highveld to below 500 mm in the Lowveld. Temperature variations also follow the altitudinal gradients, the Highveld being temperate and seldom hot, while the semi-arid Lowveld can record temperatures of up to 40ºC during summer.

5. FOREST FIRES IN SWAZILAND

5.1 Policies and Practices

Together with thunderstorms and drought, forest fires are one of the most frequently occurring and pervasive natural hazards in Swaziland, causing severe damage to the country's economy as well as to the natural and human environment. Dlamini (2005, 2007) has recently investigated the fire management practices and achievements of Swaziland. In Swaziland, fire is recognized as a management tool both in the forestry and agricultural sectors and is often used to facilitate pasture regeneration and in clearing vegetation for farming and settlements (Dlamini, 2005). Most of the burning that takes place in the wooded areas and grasslands is aimed at improving grazing conditions (Dlamini, 2005). However, there is evidence that these fires are used recklessly and proper fire regimes for Swaziland are not yet fully known. The wildland-urban interface problem is also more commonplace now than in the recent past. Urban development towards wilderness areas in such major cities as Piggs Peak, Mbabane and Manzini and other towns adjacent to forested or vegetated areas has exposed people and property to forest fires and increased the risk of damage. The wildland-urban interface fires are more complex to fight, due to the mixture of different fuels (forests and other vegetation) and structures (buildings/settlements) in the interface. This requires concerted fuel load management efforts and the formulation of policies and relevant legislation in order to minimize the negative impacts of such fires. Several attempts have been made and continue to be implemented in both the public and private sectors.

Forest fires have traditionally constrained the development of forestry in Swaziland by hindering forest companies and the society in general from obtaining significant benefits from the investment made. To minimize losses due to fires, plantation forest companies have been designed with networks of fire breaks, which are burnt annually (especially between June and July) to provide a clean belt around the forest compartments (Dlamini, 2005). Some protected areas or national parks also implement early dry season burning policies in the form of fire belts and block burns to counter stray fires and to reduce fuel load, whilst at the same time facilitating the removal of moribund vegetation. This is usually done between the months of June and September. Even with these precautions, such protected areas are not spared from fires. One such protected area, Malolotja Nature Reserve in the north-eastern part of the

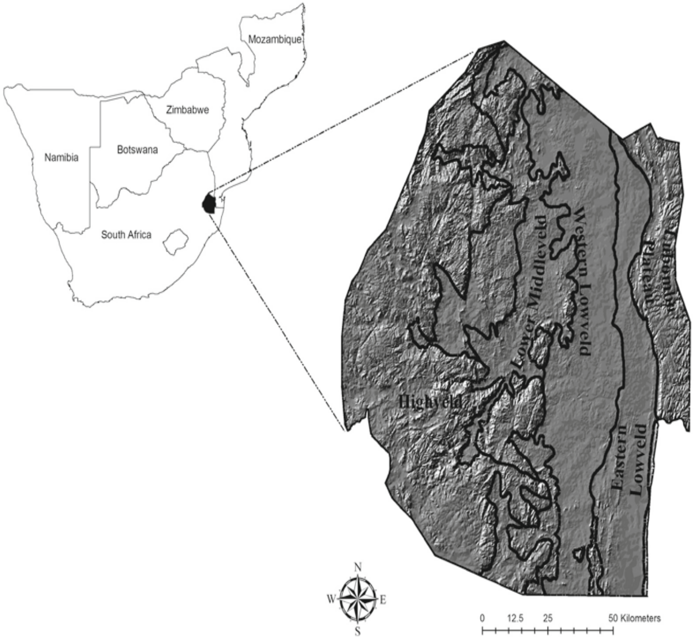

Fig. 2 Location of the Kingdom of Swaziland.

country, experiences regular dry season fires, most of which are a result of arson from poachers and neighboring communities. Lighting also occasionally triggers some of these fires within this protected area during the late winter/early summer season, but these are usually smaller in size and affect only smaller areas (personal observation).

The fire management policy framework of Swaziland—which in essence is not different from the other colonial and fire suppression policies generally adopted in Sub-Saharan Africa— has centered its attention on solutions to the fire problem that can only be effective in the short-term, no matter how sound and systematic their implementation is. For instance, an outdated Grassland Fires Act of 1955 stipulates that the burning of grass or other vegetation on land not cultivated or needed for cultivation requires the issue of a permit from the Director of Agriculture. The Act does not, however, apply to cultivated land such as plantation forests or sugarcane plantations and does not take into account the current land use systems, and the existing climatic and ecological conditions. National Fire Services Order No. 14 of 1975 establishes the Swaziland Fire and Emergency Services, which is responsible for fire-fighting and for attending to emergencies. The National Forest Policy of 2002, in turn, proposed that local Fire Prevention Units should be established in all chiefdoms and on all private farms. Such bodies are to be tasked with developing fire prevention and fire fighting strategies, in close co-operation with neighboring land users and the traditional and national authorities. Unfortunately, this was not implemented or converted into law for enforcement and, as such, these structures have not been established. The Swaziland National Trust Commission Act of 1972 also prohibits the willful or negligent cause of forest fire in a park or reserve. Similarly, the Game (Amendment) Act of 1991 prohibits willful or negligent cause of forest fires in protected areas. The Private Forests Act of 1951 contains few sections relating to forest fires and forest management. For instance, it establishes the legal need for fire belts around private forests. It is evident that the various pieces of legislation related to wild fire management are fragmented and outdated resulting in the continued negligent use of fire and numerous uncontrolled forest fires. The lack of effective policy and legislative and institutional frameworks for forest fire management is of serious concern.

5.2 Spatio-Temporal Patterns: Evidence from Remote Sensing Data

The MODIS instrument on-board Terra and Aqua satellites has 36 spectral bands spanning from the visible to the thermal infrared regions. The thermal bands in the 3 to 4 μm (e.g., bands 21 and 22) and 10 to 13 μm (e.g., band 31) wavelength regions of the electromagnetic spectrum are particularly useful, coupled with the higher sensor saturation level and better geolocation accuracy which enable more reliable detection of active fires compared to earlier and other sensors (Justice et al., 2002; Giglio et al., 2003). The standard fire hotspots detection algorithms developed for MODIS are also based on the conventional two-band thresholding method which uses both fixed and adaptive thresholds for fire detection (Kaufman et al., 1998; Justice et al., 2002; Giglio et al., 2003). The MODIS instrument is also used to map burned areas using an algorithm that takes advantage of the spectral, temporal, and structural changes using a change detection approach (Roy et al., 2005). It detects the approximate date of burning at 500 m by locating the occurrence of rapid changes in daily surface reflectance time series data and requires the consistently calibrated and processed MODIS data provided by the NASA MODIS land production system (Roy et al., 2008). The MODIS data are used to ascertain the spatial and temporal distribution of forest fires in Swaziland. The data were obtained from the Fire Information for Resource Management System (FIRMS), an integrated data system developed under NASA's Applied Sciences Program for easy access to MODIS active fire data to natural resources managers around the world (NASA/University of Maryland, 2002).

Figures 3(a) and (b) illustrate the spatial occurrence of fires and burnt areas in the country as determined by the MODIS sensor. The most evident clusters of fires are on the western part of the country largely from grassland fires and plantation forest fires where the Peak Timbers and Sappi Usuthu companies reportedly lost tens of millions of US dollars worth of property. The Peak Timber Company to the north-east lost an estimated 80% of the total forest area during the July 2007 disaster. It is in the same zone where several homesteads were destroyed by the same fires. The country's plantation forests have a very high fire hazard during the winter months, especially from July through to October. These fires result mainly from uncontrolled honey collection and arson fires due to strained social relations between the forest companies and the neighboring communities (Dlamini, 2005).

This geographic distribution of the fires illustrates the spatial pattern of the current burning practices, land use and the landscape in the country. Other clusters of fire activity are very evident to the east of the country mainly from sugarcane plantations. The steep and rugged topography of the country, more especially the Highveld and Middleveld (Remmelzwaal, 1993), can often generate the hot, dry, and windy environment needed for extreme fire behavior and accelerated fire spread rates. During the time of both 2007 and 2008 fires [Figs 3(c) and (d)], gusty and dry conditions were prevalent in the country creating perfect conditions for fires (Dlamini, 2007, 2009). The observations, therefore, indicate that these eco-climatic zones are riskiest in terms of forest fire disasters under such conditions and as such fire disaster management should pay particular attention to these areas. There is also an observed evidence of transboundary fires between Swaziland and South Africa particularly on the south-western part of the boundaries [Figs 3(c) and (d)]. It is important to observe from Figs 3(c) and (d) that both the 2007 and 2008 fires in Swaziland occurred during the same day as in neighboring South Africa where there were also reports of extensive damage and loss of human lives. This illustrates the transboundary nature and impacts of forest fires irrespective of the source of ignition.

A temporal analysis of both the MODIS active fire and burnt area data shows that the country had anomalously high fire incidents in 2007 and 2008 as compared to the previous years (Fig. 4). These are confirmations of the two extreme and disastrous fire events that the country experienced consecutively in the years 2007 and 2008. The 2007 fire was considered the worst fire experienced on record in the country resulting in it being declared a national disaster. More than 80% of the active fires in 2007 were concentrated in the plantation forests and sugarcane fields with widespread but scattered incidents in bushveld and grasslands (Dlamini, 2007). Although the 2008 reports from the Swaziland National Fire and Emergency Services have not been analyzed, the 2006 and 2007 reports indicated that a substantial amount (approximately 80%) of all fires reported were in the "Grass and Woodlands" category of fires and rest within the dwellings and industrial buildings category (Swaziland National Fire and Emergency Services, 2007).

The greatest chance of large and economically destructive fires occurs when the fuels have reached maximum quantity, are continuous over a large region, are in an extremely dry state, and are subject to a strong dry wind in an unstable atmosphere (Gill, 2005). Meteorological indications had earlier suggested that anomalous drought conditions would occur during the years 2007 and 2008. This proved true when the national government declared the drought a national disaster and since then, a lot of focus from the government was centered on providing food and water for drought victims unaware that other big and destructive disasters were looming (Dlamini, 2007). Research and results from several climate models suggest that El Nino-like conditions are likely to become more frequent in the future which subsequently means that fires in the near future will become the forerunners of larger disasters (Flannigan et al., 2005). Long drought periods contribute to the desiccation of living vegetation, dryness of large-diameter dead fuels on the ground and the elimination of the soil's effect on dead surface-fuel moisture thereby increasing the regional continuity of fuels and the chances that forest fires will spread more widely and be harder to

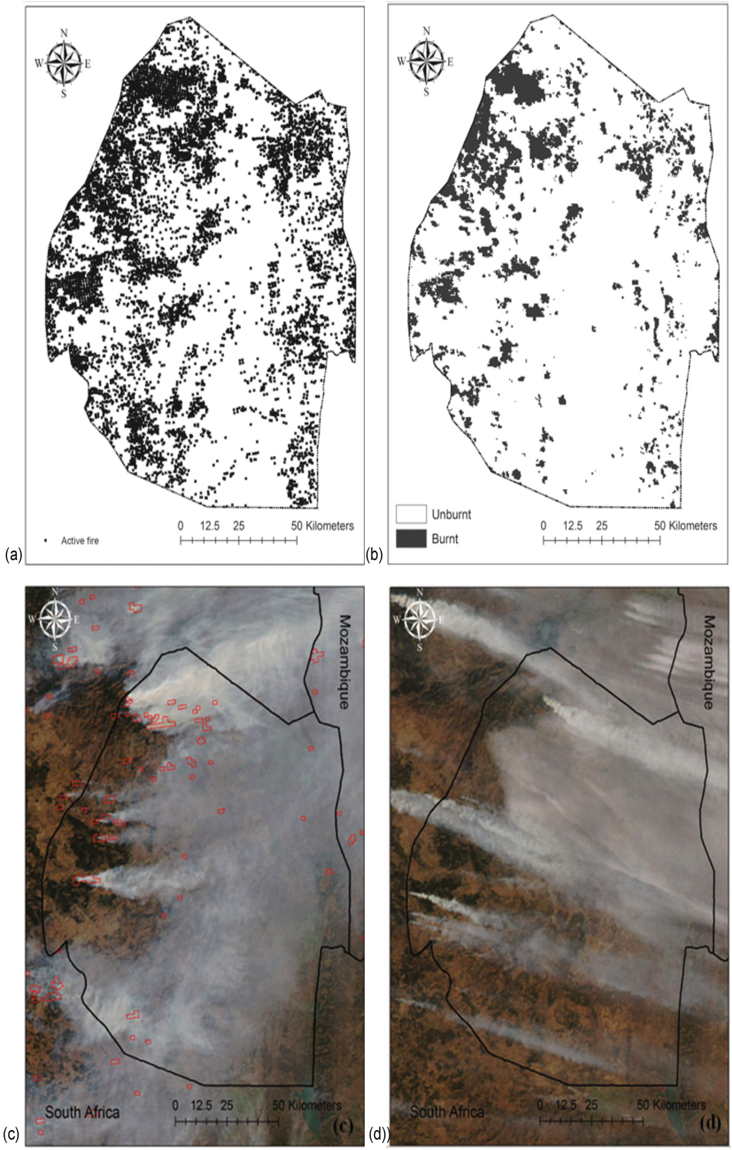

Fig. 3 MODIS active fires (**a**) and burnt area (**b**) for the period January 2003-November 2008, and the MODIS (Aqua) satellite images 28 July 2007 (**c**) and 31 August 2008 (**d**).

control (Gill, 2005). The risk of drought and fires in southern Africa has also been observed to increase dramatically in El Nino years (Anyamba et al., 2003; Riano et al., 2007).

Both the burnt area and active fire data from MODIS (Fig. 4) reveal that the fire season typically runs from May to November with a peak in August, which is an indicator of the country's temporal forest fire risk profile. Using the normalized difference vegetation index (NDVI) as an estimate of vegetation water stress, and hence fire risk, Dlamini (2007) reported a negative NDVI deviation trend from the 2001-2007 mean due to the persistence of the El Nino-like conditions which results in increasing forest fire risk. The persistent low values of NDVI obtained in the periods of 2006-2007 could, therefore, have been indicative of the looming disasters as manifested by the biggest fires ever recorded in the country. This illustrates the effects of the El Nino, especially considering the high risk associated with the phyto-physiognomy of grasslands and plantation forests in the areas affected.

5.3 Socio-Economic and Environmental Impacts

Although the study of the use of fire is increasing in importance, research on the evaluation of impacts of fire is not common. This is due to the fact that fire generates a great variety of costs that not only have private effects, but also affect society and are difficult to quantify (de Mendonça et al., 2004). Fires are also an important ecological factor, having a number of effects on the terrestrial and atmospheric environments. Scholes et al. (1996) observed that in savannas, fire suppression can cause increase in woody plants with respect to grass plants (bush encroachment), while repeated late dry-season fires can lead to a decrease in woody vegetation and an increase in grasslands. Altering burning frequency, together with climatic and edaphic factors, has been observed to modify accumulation rates of carbon in biomass and soil and influence species composition and spatial distribution of forest ecosystems (Bond et al., 2003). Impoverished soils, in turn, produce less biomass and render natural regeneration less successful exposing the soil surface to excessive runoff and the erosion of upper layers. This may lower infiltration

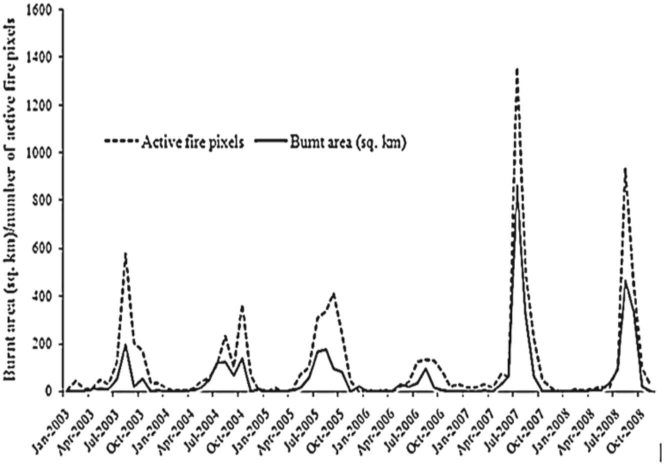

Fig. 4 Temporal variation in MODIS active fires and burnt area between January 2003 and November 2008 in Swaziland.

and keep the water table deeper, making the growth period shorter and eliminating drought susceptible vegetation and degrading wildlife habitat.

Apart from their contributory effects on the global earth system, the 2007 and 2008 forest fires and haze had regional, national and local impacts through multiple and widespread effects on health, transportation and tourism industries in Swaziland and neighboring countries, South Africa and Mozambique. During these fires (as shown in Figs 3(c) and (d)), visibility was adversely affected, bringing traffic to a standstill in some areas. The local press reported some tourists turning back at one of the country's border posts with South Africa after seeing the smoke from the forest fires. The net economic impacts were therefore significant. As a result of the observed health impacts of forest fires, the World Health Organization (WHO), in conjunction with the United Nations Environment Program (UNEP), the World Meteorological Organization (WMO) and Institute of Environmental Epidemiology (Singapore) published the first guidelines for forest fire events (Schwela et al., 1999). The extent and frequency of forest fires discussed in the preceding section point to the possible pattern of emissions from the Swaziland forest fires and the ecological and socio-economic impacts that these might have. Although not quantified in this analysis, based on the observed spatial and temporal patterns, it is important to discuss the possible impacts of such fires.

The social and economic effects of forest fires characteristically manifest through property loss (e.g., buildings, personal property, and timber), fire-fighting costs, injuries, and loss of life. Millions of dollars worth of forest plantations have been lost over the years as a result of forest fires in Swaziland. The July 2007 and August 2008 wildfires put at stake the jobs of hundreds of workers and the profitability of the plantation companies, Peak Timbers and Sappi Usuthu and other smaller companies. Reports from the Swaziland government indicated that some homesteads lost entire homes (169), property, food and cattle, goats and chickens in the fires including the loss of two lives, more than a dozen injuries and a total of 938 people affected (Dlamini, 2007; MORDYA, 2007). The plantation forest industry lost an estimated R465 million (US$45 million) of forests, 20,280 ha of plantation forest, mainly pine and eucalyptus (for sawlogs and pulpwood) comprising 19,000 ha and 1,240 ha of forests planted with pine and eucalyptus, respectively. In addition to the direct losses, the livelihoods of 21,100 people were put at risk resulting from the 728 direct and 4,368 indirect job losses incurred (Godsmark, 2007). In addition to factors that influence fire behaviors such as fuels, weather, and topography, the location and design of infrastructure and the construction materials used are critical in determining the vulnerability of communities to forest fires. These factors make the houses built in rural Swaziland particularly vulnerable to forest fires.

Another large wildfire event in late August/early September 2008 resulted in the loss of more plantation forest and more than 100 homesteads were affected including the loss of one life and several injuries. The widespread smoke from these fires is evidence of the amount of emissions released into the atmosphere and it covered a large portion of the country resulting in intense air pollution and reducing visibility in many areas. The 2008 season in most parts of southern Africa was also devastating with other countries such as Botswana experiencing fires covering three million hectares; South Africa and Swaziland losing thousands of hectares of valuable timber plantations and hundreds of thousands of hectares of grazing grounds, bushveld and savannas. These fires also ravaged settlements and other property damages estimated in the hundreds of millions of Emalangeni (Rands). Two human fatalities and countless injuries were also reported in the 2007 inferno which was eventually declared a national disaster on August 1, 2007 by the country's Prime Minister. The 2008 event resulted in one fatality and more than 100 homesteads were destroyed in Swaziland. All the impacts are not known yet, but it is evident from Figs 3(c) and (d) that there were significant emissions from the smoke.

The use of fire in Swaziland also generates negative externalities for society, among which are damages identified with CO_2 emissions into the atmosphere, genetic resource losses, and human health damage provoked by smoke. Other negative effects that were experienced included traffic/transportation delays, power failures, and recreational losses. The health impacts of biomass smoke episodes have been extensively reviewed (Arbex et al., 2004) and show the adverse health effects associated with particles from combustion of biomass including wood, other vegetation, animal wastes, sugar cane, etc. Since particulate matter produced by incomplete combustion of biomass is mainly less than 1 μm in aerodynamic diameter, both PM10 (particulate matter with an aerodynamic diameter less than 10 μm) and PM2.5 (aerodynamic diameter less than 2.5 μm) concentrations increase during air pollution episodes caused by vegetation fires (Arbex et al., 2004), which can also be transported to great distances. Nearly 200 distinct organic compounds have been identified in the wood smoke aerosol from biomass burning, including polycyclic aromatic hydrocarbons which are known to be linked to increased mortality and morbidity in susceptible persons, and increased risk of hospital and emergency admissions (Schwela et al., 1999).

In Swaziland, as in much of the world, patterns of development are superimposed on patterns of forests and other vegetation in ways that may amplify the consequences of forest fires. In the Lowveld, for example, agricultural growth and sugarcane expansion are often much greater at low elevations and so is the case in the higher, grassland and plantation-forested elevations of the Highveld. Given that Swaziland's population density is increasing in high-risk areas, additional infrastructure investment may fail to offset the increased danger. For example, fire-fighting resources are already diverted to protecting structures in high population-density zones at the expense of the capacity to control the growth in fire perimeter, resulting in larger fires. If present development trends continue, the economic impact of additional forest fires could very well be substantial. While the acceleration in settlements into areas with fire-prone vegetation is an important driver of this upward trend, there are suggestions of the observed increases resulting from a combination of climate change, land use practices and demographic factors (Dlamini, 2007, 2009). Even with no augmentation of fire-fighting mechanisms, fire-fighting costs will also increase as climate change accelerates the development of fires to higher dispatch levels where more expensive resources (e.g., water tankers and bulldozers) will be routinely utilized. Added to this are the possible extensive losses of urban infrastructure (e.g., telecommunication, water, electricity, and transportation systems), the costs of which are likely to be borne largely by local and national government and finally translating to individual costs.

6. MONITORING OF FOREST FIRE AND EARLY WARNING SYSTEM

The efficient management of disasters currently postulates a more generalized as well as integrated approach. The social intervention in such cases requires the relevant application of acquired scientific knowledge and technological achievements based on rational design and adequately organized operational actions. Public and operational agencies involved in disaster management have long recognized that many critical problems faced on an operational level are of endogenously spatial nature. For this reason, spatial information and data constitute an important framework of analysis when dealing with disaster management problems. In the case of forest fires, the need for early fire detection varies according to numerous factors.

Similar to other disasters, forest fires constitute a threat when they occur on either fairly populated regions or areas of high ecological or economic value. Therefore, the urgency for forest fire detection and fire-fighting changes according to the nature of the fire. For instance, natural fires need not be extinguished but can only be extinguished when they are considered a threat to human assets. Human-caused fires, on the contrary, are often extinguished as soon as possible implying that early detection of these fires is clearly aimed at fire-fighting. Therefore, it is assumed that early detection is only needed when fire-fighting or fire control resources are available. An analysis of the requirements of the fire suppression community for early fire detection in Europe resulted in a maximum detection time of 15 min from the start of the fire (INSA, 2000), thereby indicating that the value of the information on fire detection decreases according to a negative exponential curve (San-Miguel-Ayanz et al., 2005). This can be easily explained by the fact that fires are usually easy to extinguish at an early stage; once a fire has reached a fairly large size, operations for fire-fighting become very complicated and the control of the fire depends largely on the meteorological conditions that determine fire spread. In sparsely populated areas, where fires are not extinguished, fire detection is only needed for monitoring environmental impacts. Early detection is therefore often not necessary in such areas.

The continuous monitoring of forest fires involves the observation of active fires and forest fire-causing processes (fuel types and fuel conditions), forest fire risk assessment, mapping of burnt area and fire effects and countries with significant forest fire activity have developed ground- and air-based monitoring networks (San-Miguel-Ayanz et al., 2005; Chuvieco and Kasischke, 2007). However, due to economic and technological difficulties, developing countries such as Swaziland are still lagging behind in taking advantage of such technologies. The emergence of satellite remote sensing provides opportunities for the continuous and large-scale monitoring of forest fires, which may overcome the logistical and financial constraints of ground-based and air-borne observations. Geographic information systems (GIS) and remote sensing technology have been developed in such a way that spatial information is stored and efficiently retrieved and modeling techniques are appropriately embedded to support decision making and operational needs. The added value of GIS technology usage in managing emergencies is directly connected to the benefits expected from the exploitation of such technologies designed for supporting decision-making related to the geographical space, especially in the case of the operational field that intensely needs to make important decisions of spatial nature.

Remote sensing instruments on polar-orbiting and geostationary satellites allow forest fire observations at a broad range of spatial and temporal scales. These satellite-based fire and thermal anomaly detection systems are indispensable for both research and operational use. Satellite instruments that can simultaneously utilize 3.9 μm and 11 μm channels can be used for fire detection due to the 3.9 μm channel's strong thermal sensitivity even if only a small portion of the pixel is covered by fire (Matson and Dozier, 1981). For a long time, including the present, operational systems have been using data from the NOAA Advanced Very High Resolution Radiometer (AVHRR) and GOES (Geostationary Operational Environmental Satellite), including a few others such as the DMSP-OLS (San-Miguel-Ayanz et al., 2005). Remote sensors (e.g., MODIS and MSG-SEVIRI) have been implemented and are operationally used to complement the human visual detection available in most of the ground detection systems such as watch towers, as operational fire detection still relies on human surveillance. However, there is still a considerable gap between research and operation.

Few examples exist in which satellite systems are integrated into operational fire detection and alert systems. Two of these examples are the FIRMS and the Advanced Fire Information Service (AFIS) systems, which are also useful for forest fire management in Swaziland. Both are satellite-based real-time observation and alert systems for forest fire management. The FIRMS system is a result of a collaboration effort between the University of Maryland, NASA, FAO and Conservation International. Within the FIRMS system (Fig. 5), global MODIS data are processed in near-real-time by the MODIS Rapid Response System, active fire locations are generated using a global thermal anomalies algorithm (MOD14) and these fire coordinates are ingested into FIRMS from where they are made available in a number of formats including a web mapping interface called *Web Fire Mapper* (a new open source

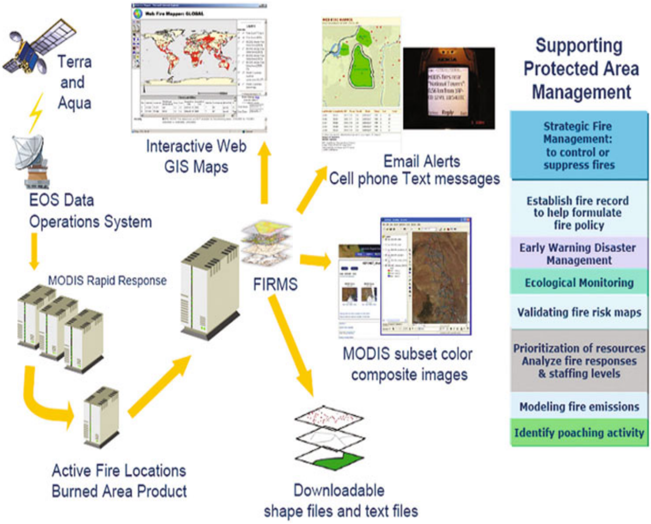

Fig. 5 FIRMS system architecture for active fire mapping (NASA/University of Maryland, 2002).

software-based system called *Firefly* is being tested), as email alerts, text files, ESRI shape files and through files that can readily be viewed in virtual globes such as Google Earth, ArcGlobe and NASA World Wind. FIRMS contributes to the Global Terrestrial Observing System's (GTOS) Global Observation of Forest and Land Cover Dynamics (GOFC/GOLD) program, which seeks to promote improved access to, and use of, satellite data products.

The AFIS system is a joint initiative of South Africa's Council on Industrial Research (CSIR) and the electricity company Eskom. The *AFIS* system, which is based on the combined use of the MODIS and MSG SEVIRI sensors onboard of the NASA and ESA satellites respectively, works operationally in South Africa and covers the whole of Swaziland. Both the *FIRMS* and *AFIS* are stable, reliable, and send email and mobile phone SMS alerts when fire detection occurs (Fig. 6). These systems permit the coverage of a very large area at a relative low-cost, with combined detection rates of up to 70%, and can enable airborne surveys to be directed to critical areas (Frost and Vosloo, 2006). AFIS and FIRMS are an example of how new technology can be incorporated into operational systems for improved forest fire monitoring as currently being utilized (although at a limited scale) in Swaziland.

As sensors for forest fire detection and monitoring improve, and information and communication technologies advance, the capabilities to ingest, process and transmit large amounts of data in (near) real-time are becoming a reality. The development of algorithms for active fire detection and burnt-area mapping and monitoring is also fairly advanced, which brings automatic forest fire surveillance from satellites closer to being realized. It is only required that future satellite missions such as the NPP/NPOESS Visible Infrared Imagery Radiometer Suite (VIIRS), NPP/NPOESS Visible Infrared Imagery Radiometer Suite (VIIRS) and sensors onboard the Global Monitoring for Environment and Security (GMES) provide data with enough frequency to minimize the re-visit time to forest fire risk areas. San-Miguel-Ayanz et al. (2005), Chuvieco and Kasischke (2007), and Qu et al. (2008) provide good overviews of the capabilities and limitations of remotely-sensed data applications for fire emergency management.

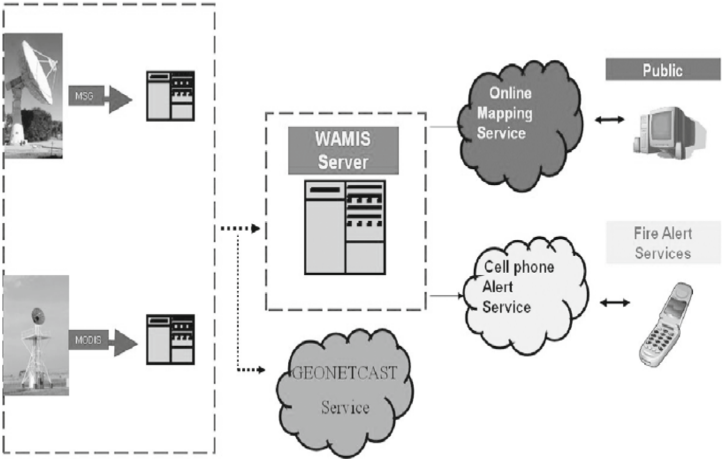

Fig. 6 Schematic of AFIS sensor web architecture (CSIR, 2008).

One of the common shortcomings of space-borne instruments is the lower limits for fire sizes that they can detect and the incapability of detecting fires through clouds or thick smoke. Polar-orbiting satellites, on one hand, cannot see short-duration fires that take place between the satellite overpasses; on the other hand, geostationary satellites have better temporal resolution, but worse spatial resolution and have difficulties when scanning at high viewing angles (Dlamini, 2009). Moreover, caution needs to be taken and considered with remotely-sensed fire observations because the daytime radiance signal at 3.7 mm may be a combination of both emitted thermal, hot background surfaces and a reflected solar radiation which may produce false fire alarms and/or saturate the 3.7 mm channel (Di Bisceglie et al., 2005; Gao et al., 2006). Active fires from polar-orbiting satellites also represent a limited temporal sample due to the satellites' restricted overpass frequency, coupled with the diurnal fire cycle (Hyer et al., 2007).

Despite the advances in forest fire detection and monitoring technology, there is a need for continued coordination to continue improving access to near real-time and archived fire data and its use for resource managers, policy-makers and the scientific community, and to secure long-term fire observing systems from which developing countries such as Swaziland can immensely benefit. The fire theme of Global Observation of Forest Cover/Land Cover Dynamics (GOFC-GOLD) is actively working on the harmonization of remote sensing and in situ observations of forest fires including the development of capabilities for periodic global assessments of fire, capacity building for space-based fire observations, development of a global early fire warning system and a global fire monitoring network from geostationary satellites. In accordance with the United Nations International Strategy for Disaster Reduction (UN-ISDR), the Germany-based Global Fire Monitoring Center (GFMC), the Global Wildland Fire Network and the UN-ISDR Wildland Fire Advisory Group (both of which are coordinated by the GFMC), are also working on improving fire management capacity around the world. Other initiatives include Fire Management Actions Alliance established in May 2007 during the 4th International Wildland Fire Conference in Seville, Spain and based in Rome, Italy under the auspices of the Food and Agriculture Organization.

7. STRATEGIES FOR MITIGATING FOREST FIRE HAZARDS

It seems evident that Swaziland will most likely face the same catastrophe with certain periodicity in the future, unless even better mitigation strategies are established. However, the main problem in applying efficient mitigation measures is the size of the affected area and the cost involved. On the other hand, an important part of the budget has still to be destined to suppression of fires while new policy results are not yet visible, and the real causes are eradicated. It is clear that there are many threats to Swaziland's people and assets as well as many challenges and potential opportunities for the future. The establishment of the Swaziland Fire and Emergency Services and improved planning procedures in the twentieth century, as well as a continuous increase in fire pre-suppression and suppression expenditures did stabilize the burned area in 'acceptable' levels until recent times. The number of forest fires has however remained high, hence denoting failure in preventing fire occurrence because no fire management program can be economically effective when the number of fires is so unregulated. It adds that in the 2007-2008 periods, most of the disastrous fires in Swaziland were of unknown origin, which constitutes an obvious obstacle to defining sound mitigation strategies.

Swaziland's national fire policies have mainly focused on fire suppression and paid very little attention to fuel management thus resulting in an increase of accumulated fuel load and forest vulnerability to fire, setting the scene for larger and more damaging fires even in the future. It is a fact that fire control technology can tackle just a small fraction of the potential intensity of a fire (Gill, 2005). In the Swaziland fires of 2007 and 2008, the limitations of fire fighting were further aggravated by the extent of the wildland-urban interface and capability to halt the spread of the forest fires was seriously diminished when the rough topography and dry, abundant fuel concurred with extreme weather. Fuel management programs, if properly designed and implemented, can reduce the severity of forest fires under any weather and increase the weather thresholds for effective fire fighting (Fernandes and Botelho, 2003). This is the strategy that has been used in the protected areas of the country. Fire suppression and fuel management can, therefore, be thought of as two sides of the same coin. Allocation of the budget between these complementary activities in the framework of a balanced and successful fire management policy is the major challenge. Incoll (1994) indicated that the total costs of fire management and damage caused by wildfire is minimized when the fuel management expense exceeds the cost of fire suppression by a factor of three. However, the above basic question has not received much attention in Swaziland in the past and requires additional research.

Within this context, the interest of having better fire prevention and assessment tools should be emphasized. Fire risk assessment is a critical component of fire prevention, since pre-fire planning resources require objective tools to monitor when and where a fire is more prone to occur, or when it will have more negative effects (Chuvieco et al., 2009). As happens in connection with other kinds of natural risks, forest fire hazard assessment can take place starting within three different conceptual frameworks: static risk assessment, dynamic risk assessment and real time risk assessment (Fiorucci et al., 2005). This involves the evaluation and the risk distribution over the geographical space is carried out on the basis of static or dynamic information (e.g., topography, vegetational cover) and taking into account the main variables involved in the considered process (i.e., fire occurrence, weather conditions and land use). The purpose of forest fire risk assessment could be that of planning the sizing and location of the different kinds of resources and infrastructure necessary to manage forest fire risk over a wide area. This is particularly important in this era of global change, where climate change continues to exacerbate the severity and impacts of forest fires. Unfortunately, forest fire risk assessment is another aspect of forest fire management that has not been addressed in Swaziland. Krawchuk et al. (2009) propose that the expected changes in forest fire activity due to weather conditions need to be integrated with forest landscape models to further understand the complex outcome of the various interacting factors.

One of the most effective approaches to safeguard against the inherent risk of a forest fire disaster is to decrease the community's vulnerability through appropriate mitigation measures. As stated earlier, the current mitigation measures used include systems of fire breaks within plantations and protected areas and controlled block burns. However, an effective disaster mitigation program must include aspects of public awareness, capacity building, and multi-disciplinary collaboration. Public education and safety promotion programs are key components of a successful disaster response which must be developed. In order for the public to be prepared even to a minimal standard, the forest fire disasters that the community may face must be common knowledge. Additionally, the community must be made aware of simple actions that can reduce an individual's personal vulnerability. Unfortunately such measures are least implemented in Swaziland except for ad hoc radio broadcasts during the forest fire season.

Forest fire prevention and mitigation requires knowledge about the weather, ecology, and terrain of an area, the infrastructure for monitoring, road networks, the ability to mobilize and train human resources, and appropriate information, communication and telecommunications infrastructure, all of which are scarce in sub-Saharan Africa. A few African countries, such as Ethiopia and South Africa, have fire danger warning systems. Although the country has relatively good infrastructure, Swaziland does not currently have a fire danger system in place and this needs to be developed as a matter of urgency given the increase in the number and severity of forest fires. The use of satellite data to monitor burnt areas for purposes of estimating biomass-related greenhouse gases has been introduced in some African countries. In support of this, the Southern Africa Fire Network (SAFNet), of which Swaziland is a member, provides a framework for exchanging fire management information and for capacity building, with the emphasis on the use of geo-spatial information technologies. The Global Fire Monitoring Centre (GFMC) also covers forest fires in Africa. The FIRMS and AFIS databases can and will then be used to undertake seasonal assessment of fire risks for different parts of the country, which could be used to develop mitigation strategies in future.

While unprecedented amounts of fuel have accumulated, the population of Swaziland has also shifted temporally and spatially. More and more people are living in or near areas prone to forest fires. In recent decades, the population has also become more dispersed thus increasing the number of people living in heavily vegetated areas where wildlands meet urban development (i.e., wildland/urban interface). The result is increased risk to more homes and other structures, and together with the accumulation of fuel and development in hazardous areas, this poses particular challenges for the insured and insurers as well as the government agencies responsible for fire prevention, mitigation and suppression.

8. CONCLUSIONS AND RECOMMENDATIONS

Fire is one of the disasters causing threats to the forests and the ecosystem from a local level to a global level. Forest fires have adverse effects on the natural environment and humans such as experienced in Swaziland in the disastrous forest fires in the years 2007 and 2008. As revealed from the remote sensing data, both the 2007 and 2008 extreme forest fires occurred at the same time with the South African fires, pointing to the need for a coordinated international approach in the management of forest fires.

In a broad perspective, the challenges and their proposed solutions to forest fire management in Swaziland generally fit into two categories. The first category consists of socio-ecological challenges associated with the accumulation of fuel load and population growth in the areas prone to forest fire. The solutions to those challenges involve mitigating potential losses through increased understanding of fire behavior, public education, improved national and interagency collaboration, capacity building, fire-safe building codes, land use planning, and investment in modern early warning and monitoring technologies including geospatial technologies. The second category consists of the risk decision challenges insurers face in underwriting properties exposed to the forest fire hazards. The solutions to these challenges include: developing and implementing appropriate underwriting guidelines; measuring and managing the aggregate amount of forest fire exposure in an insurer's book of business; managing the geographic distribution of exposures to prevent excessive concentration in any single area or contiguous areas prone to forest fires; and educating agents and the insured about loss mitigation. In both the categories of challenges, Swaziland's newly established Disaster Management Agency should play a key role in ensuring that the proposed solutions are implemented.

Forest fire risk assessment in Swaziland has not been undertaken. This needs to be done as a matter of urgency using remotely sensed data and other spatial data to better quantify values and risks as well as suppression capability. The obtained forest fire risk maps can then be used by the Disaster Management Agency and other decision-makers in making tactical decisions on prioritizing prevention measures. These maps can also give an indication of forest fires on a long-term basis and they can be utilized by decision/policy-makers to protect areas prone to forest fires in line with the Hyogo Framework for Action 2005-2015 (HFA).

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