

# **FOREST FIRE RISK MODEL FOR MICHOACAN, MEXICO**

Sonia Juarez Orozco  
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# FOREST FIRE RISK MODEL FOR MICHOACAN, MEXICO

by

Sonia Juarez Orozco

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Thesis Assessment Board

**Prof. Dr. V. G. Jetten** (Chair)

**Dr. A. Velazquez** (External examiner)

**Dr. Y. A. Hussin** (ITC supervisor)

**Dr. J.F. Mas** (Mexican supervisor)



INTERNATIONAL INSTITUTE FOR GEO-INFORMATION SCIENCE AND EARTH OBSERVATION  
ENSCHDEDE, THE NETHERLANDS

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## Abstract

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The incidence of fires in size, frequency and intensity has increased significantly around the world. Mexico, a mega diverse country, has recurring forest fires, especially on the El Niño years. However, the government efforts for fire prevention are still insufficient to reduce fire frequency and intensity. Moreover, the generation of fire risk maps is still lacking for the major part of the country. Mexico needs to develop, with high efficiency, fire prevention strategies, in order to avoid the loss of natural resources. As any other natural disaster, fires have always influenced ecosystems provoking important abiotic and biotic changes. However, not all the ecosystems are adapted to the increasing frequency and size of forest fires. Fires cause the loss of local biodiversity and grave socio-economical damage. In Mexico, Michoacán state is among the first states with high fire frequency. Human activities such as grassland burning or campfires are the main cause. The general objective of this study is to model forest fire risk for a critical zone in Michoacán state. In order to do this, the method was divided in three phases: exploratory, modelling and validation. This study integrates biophysical and human variables into a fire risk model. There are four main factors that modify the fire risk model: 1) fuel, 2) physical environment, 3) causal factors and 4) prevention and suppression. Out of these factors, fuel is considered as the most important since is indispensable for fire ignition and spreading. In the first phase, these effecting factors were analyzed statistically. Likewise, in this phase, an ASTER image was used for visual interpretation to generate a burnt area map and to improve the vegetation type map. In the second phase, in order to detect the high, medium and low risk areas, five sub-models were developed: Fuel, Ignition, Detection, Response and Weather. These sub-models were constructed using logical indices based on literature review and expert opinion. Finally, in the third phase, the fire model was validated with a burn area map of the study site. The final outputs were a static fire risk model and twelve weather monthly risk models. The knowledge of the fire risk areas allow us to recommend the development of fire prevention plans.

The study revealed that factors included in the fuel and ignition sub-models play an important role to determine the fire risk. The vegetation types with more burnt surface were: Oak forest, Scrubland and Pine forest. The distribution of the burnt areas also shows a tendency on elevation, aspect and slope classes. Burnt areas were predominantly over medium altitudes, oriented to south and on steep slopes. Results also showed that in the proximity of crop fields, grasslands and road there is more burnt surface, but as this distance increases the burnt surface decreases. On the other hand, the detection sub-model revealed that a high percent of the study area is visible from cities, roads and forest towers. For fire risk management plans however, it is worth to consider the non visible areas. According to the Response sub-model 36.2% of the study area has a high to maximum response, 42.3% shows a medium to moderate response and 5.6% may have a low to minimum response. The results of the sum of these sub-models in its static version show that 91% of the forest's surface is in the medium high to high risk categories.

**Key words:** Forest fire, Fire risk, Fuel, Ignition, Weather, Detection, Response, México, Michoacán

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# 1. INTRODUCTION

## 1.1. Background

### 1.1.1. Forest fires and influencing factors

A fire is a chemical reaction that needs heat, oxygen and fuel to start and carry on, as it is established in the “fire fundamentals triangle”[1]. When an uncontrolled fire starts in or spreads to natural vegetation it converts to a forest fire. Therefore, the probability of occurrence of it depends on the ignition causes and environmental preconditions [2]. Among these are the fuel’s quality and distribution, and the weather, topography and human factors [3,4]. The following are brief descriptions of these influencing factors.

- *Fuel’s distribution.* Fuel could be distributed vertically or horizontally; a vertical distribution means that the fuel is found perpendicular to the ground, meanwhile, if the fuel is found in a parallel arrange to the ground, its is said that its distribution is horizontal. Often fuel’s vertical distribution is found in a very uneven way, which causes variations in the intensity of fire [4]. On the other hand, the horizontal distribution will determine where the fire will occur or spread.
- *Fuel’s quality.* The characteristics of a fire, like the intensity and the heat generated, are essentially determined by the quantity and composition of the available fuel [5,6]. Fuel could be either living organic matter (like grass, bushes, trees, or canopy) or dead organic matter (*i. e.* dead bark, branches, twigs, leaves, etc.) [5]. The arrangement, size density, distribution, moisture and chemical composition of these materials, are the factors that determines fire’s intensity. Therefore fire’s spreading speed and released energy are highly depending on the mentioned factors [6]. Such characteristics are due to vegetation type found in the areas where the fire is happening [5].
- *Weather.* High temperatures, low relative humidity, and winds are the typical weather conditions for a fire development, because these conditions reduce fuel’s drying time and the spread of fire [3]. Nevertheless, local weather is determined, in part, by the vegetation, for example a dense and close canopy reduces relative evaporation and maintains high soil humidity; yet in an area with less vegetation cover the opposite will occur [7].

- *Topography.* Terrain's shape has several effects on fire's distribution. For example in the case of a fire on a slope, the flames establish a strong contact with the ground surface, which heats up the fuel and favours the fire's spread [5]. Therefore, the movement of a fire is slower if it begins on a summit and is faster if begins on a canyon. This behaviour can also explain why a rough topography can constitute a fire-breaker barrier [8]. In addition, the slope's orientation plays a key role in fire's behaviour. This is because in the Northern hemisphere, a southern slope is drier than the northern slope. Southern slope is more suitable to be prone of ignite fire than the northern slope that has more humidity and green cover. In contrast, despite that altitude is not consider a factor that directly increases the occurrence of fire, it does modify the climate, which is a directly related factor with fires. For example, the temperature at higher altitudes is lower than low altitudes. More over precipitation is higher than lower zones. This reduces the probability of fires due to the moisture of fuel.
- *Human factors.* From human history, man has lived with fire [9,10], and man was able to control it. Fire has been used by humans for many reasons, from cooking food to agriculture or livestock farming. Due to neglect activity and misuse of fire in agriculture or grazing land management, human activities is a main cause of fires around the world and Mexico is not an exception [11,12]. Fires are also related to other indirect activities such as deforestation, use of non-timber forest products (NTFP) or socio-economic and political conflicts. Thus, the study of human's role and his/her activities is crucial to understand the distribution of fires and its control. In Mexico, from pre-columbine times to the actuality shifting cultivation or slash and-burn agriculture, has been a common practice in Mexico [13]. Each year new areas are deforested and incorporated to shifting agriculture and grasslands. This represents a real risk for the forested areas since the population; mostly the poorest sector had not instruction to control fire during the preparation of the agricultural terrain and grasslands.

### 1.1.2. Classification of forest fire

There are two forms to classify a forest fire: by its origin or by the affected fuel stratum. Each classification is useful to develop prevention or suppression actions in a forest management plan. To design a prevention plan it is important to know the origin of a fire. On the other hand, the affected fuel stratum determines in great part the behaviour and intensity of the fire. Consequently, the needed actions to control an active fire could depend on it. The main characteristics of each classification are:

- By its **origin** a fire can be classified to be started either naturally or by humans. A natural fire is usually provoked by lightning. But natural causes also can be: extreme heat, sparks

created by the friction of falling rocks or volcanic eruptions. Nevertheless, as it was explained in the previous section, the main cause of forest fire around the world is human. Forest fires caused by human can be divided into: **negligent**, **intentional** and **accidental** [14]. The main human activities that provoke forest fire in Mexico are negligence activities. Agriculture and grassland burning represent 60%. Other negligent activities can be cigarettes and camp fires (18%). Intentional fires, which represent 12% of the forest fires, occur as a product of conflicts or inadequate land use (e.g. illegal deforestation). Finally accidental fires are product of non intention action as car or train crash or electrical failure.

- Another classification is focused on the **affected fuel stratum** [15]. A fire that spreads horizontally over a terrain consuming leaves, twigs, fallen trees, grasses and other low plants is classified as **superficial** [15]. If the fire reaches the tree crowns under the influence the wind and slope, then is converted to a **crown** fire [16]. These type of fires are considered very destructive and of difficult control [17]. On the other hand, **ground** fires are those which spread below ground, burning organic matter such as compacted dead leaves and roots [15].

### 1.1.3. Forest fires: Effects and consequences

After a forest fire there are remarkable abiotic and biotic changes. Some are the direct consequence of the fire, such as bark singe or tissue disintegration. However, there are other indirect effects that remain once the fire is extinguished. The main abiotic changes after a fire are: increase or decrease in soil nutrients content [4,18,19], increase of light and soil temperature [4,18] and increase of wind speed as a consequence of vegetation removal [20]. Due to these changes soil erosion processes are usually seen after fire [21]. Unless the ecosystem is adapted to fire, the frequent presence of fire decreases the composition and alters of species biodiversity and vertical structure [12,22,23]. There can be also big socio-economic impacts. Among them wood burnt or house damages are the most frequent. In summary, among the forest fire damages can be found: 1) wood destruction, 2) increase on land erosion, 3) habitat destruction and flora and fauna lose, 4) tree weakness and illness, 5) pollutants increase, 6) decrease of landscape beauty, 7) health damages as a consequence of respiratory problems and 8) human and animal deaths [12,14,24].

### 1.1.4. Fire hazard, risk and danger definitions

A known risk definition is “the probability of an event and the expected outcome-typically expressed as damage of the event” [25]. In other words, “is the multiplication of costs, the vulnerability and the recurrence interval of natural damaging phenomenon” [26]. The last definition is commonly applied to study technological, landslides, volcanic and other catastrophic events. However, the terminology of fire danger, risk and hazard is not always completely clear as in other disciplines. The definition and use of the term fire risk varies widely

among fire researches [2]. Some authors have discussed the heterogeneity of this terminology. Bachmann, after a extensive literature review [2] proposes that: “**Fire hazard** is the process leading to undesirable outcomes”, “**Fire risk** comprises the probability of an undesired event and the outcome of it” and “**Wildfire risk** is the probability of a wildfire to occur at a specified location and under given circumstances and its expected outcome as defined by the impacts on the affected objects.” In contrast, Hardy [25] considers as wrong the catastrophic and negative adjectives associated with fire risk, since fire has always existed in the nature and even for some ecosystems it is part of a natural and recurrent process. Therefore, this author proposes that “**Fire risk** refers only to the chance (probability) of ignition of a spreading fire, and does not address values or damages”, whereas “**Fire hazard** is a fire-centric term, and is independent of weather. The term hazard must only be used to express the state of the fuel complex”. Other concept used in fire management is fire danger. FAO [27] defines **fire danger** as “A general term used to express an assessment of both fixed and variable factors of the fire environment that determine the ease of ignition, rate of spread, difficulty of control and fire impact – often expressed as an index.” Besides, it considers that **fire danger rating** is: “A component of a fire management system that integrates the effects of selected fire danger factors into one or more qualitative or numerical indices of current protection needs”.

#### 1.1.5. The role of Remote Sensing and GIS in fire modelling

Nowadays, many tools are exist which integrate the biophysical and social elements. GIS and remote sensing allow to monitor, analyze and predict forest fires activity from local to global scales [28-31]. The following points summarize RS/GIS applications in forest fires [30,31]:

- They allow to integrate hazard variables such as vegetation, topography and human infrastructure
- They help to identify fire risk areas since they can consider meteorological conditions, vegetation type and allow the burnt area detection.
- They provide important information of human settlements, natural resources, etc.
- They allow evaluating the fire disturbance degree and to asses the damages of the burnt forest.
- They allow to model forest fire risk or risk, to monitor and manage active forest fire, to model or simulate fire growth or spread and to assess forest recovery after fire.

RS/GIS are widely used for fire management including prevention activities. Remote sensing techniques allow monitoring vegetation, susceptibility to the fire, detection of the thermal signal of active fires, and post-suppression tasks as burnt area assessment [32]. The detection of active fires allows knowing the fire distribution pattern. This is particularly useful in areas which were accurate fire reports are not available. Moreover, remote sensing techniques become indispensable for big inaccessible forest areas. The study of fire after effects is another important issue that is commonly used to assess damages or study vegetation recovery. On the other hand, GIS is a suitable tool to integrate risk factors and to construct sceneries of forest fire risk. In the



next sections a brief review will focus on active fire detection, burnt scar assessment and fire risk modeling was done.

#### **1.1.5.1. Active fires**

There are several remote sensors designed to detect and monitor active fires in different spatial and temporal scales. Among these we can cite the Advanced Very High Resolution Radiometer (AVHRR), the Infrared Spin-Scan Radiometer and Atmospheric Sounder (VAS), the Along Track Scanning Radiometer (ATSR), the Moderate Resolution Image Spectroradiometer, the Operational Linescan System (OLS) and the Bi-spectral Infrared Detection (BIRD). A complete list of this sensors can be find in Lentil *et al.* [28]. The main differences among these sensors are the resolution of the MIR channel the revisit time, the minimal detectable fire area, the capability for a quantitative retrieval of fire parameters and the general mission parameter [33]. For example sensors as MODIS, AVHRR and ATSR have 1 km<sup>2</sup> of resolution and a revisit time of 12, 24, 24 hours respectively. On the other hand, BIRD sensor with its 100 m<sup>2</sup> of resolution allows the detection of fires in an area 7 times smaller than MODIS, but its revisit time is based on experimental imaging of selected areas [34]. In order to distinguish hot spots from the rest of the environment numerous algorithms have been proposed [35,36]. Basically, the detection of active fires is based on the brightness temperature levels in short wave and thermal Infrared bands (MIR, TIR, VNIR) wavelength bands which must be above the background [37]. This temperature depends on the fire temperature and size which is in function on the specific characteristics of the fire as it is the affected vegetation type and the fire intensity levels. It is worth to notice that the active fire detection still present certain problems. The main limitation is the information gap caused by the temporal coverage of most satellites, which in some cases could be every 16 days. This lack of information produces errors of commission that gives erroneous panoramas of what really happens [38]. However, the study of remote sensing is in constant development. It is probable that soon new methodologies will allow obtaining more reliable information. Some authors have proposed alternatives to this problem combining remote sensing techniques for the detection of active fire pixels with methods of burnt area detection [38].

#### **1.1.5.2. Burnt scars**

During a fire, the vegetation disappear giving place to a black layer of ash, and burnt material. The vegetation absence increases the sun exposition of the soil, increasing the temperature of the soil [18,39]. Both facts are clues for burnt scars mapping which can be done by visual interpretation [24,40] or by satellite image classification [40]. The selection of bands is crucial for good visual interpretation since burn areas present low reflectance in red and near infrared. For example, Landsat bands 4 and 5 have a good performance on the direct identification of burnt areas [40]. Based on this principle, the normalized difference vegetation index (NDVI) is

also used for mapping burned forested areas [41]. Other indices for burned land discrimination are the Burned Area Index, the Soil Adjusted Vegetation Index and the Global Environmental Monitoring Index [42]. On the other hand, surface temperature is other accurate criterion to discriminate burned areas and surroundings. The value composite technique [43] compare maximum or minimum values of different data such as NDVI, temperature, channels or albedo from different dates in order to found changes on land cover and detect burned areas. Summarizing, some of the composite techniques on satellite image classification for burned land mapping are [44,45]: 1) Minimum reflectance of the red channel and Minimum reflectance of the NIR channel, 2) Maximum Surface/Brightness Temperature, 3) Maximum value composite of the date with the maximum NDVI, 4) Maximum temperature from the three minimum reflectance for channel 2 and 5) Minimum reflectance of channel 2 from the three maximum temperatures. Among these, the composites that uses thermal bands have better accuracy than those based on NDVI values due to its capacity of cloud and shadow discrimination [46]. Moreover the Burnt Area Index, which considers a spectral reference point in its calculation, shows also a great capacity on burnt area discrimination [42]. Finally is worth to say that the product MCD45 of the Moderate Resolution Imaging Spectroradiometer (MODIS) of 500 m pixel resolution have been developed to localize and assess spatially and temporally the burnt areas [35].

### **1.1.5.3. Forest fires modelling**

According to Chuvieco [5] there are four main approaches to model forest fire risk: 1) Qualitative and quantitative models based on expert knowledge, 2) Quantitative models based on multi-criteria evaluation 3) Models based on statistics, in which are included neural network models and 4) Meteorological or fire dispersion models. The quantitative models based on expert knowledge classify the fire variables using a numeric scale based on formula indices or weights derived from field observations, literature review and expert opinion. Then, the fire risk model is reclassified into a categorical scale into high, medium and low risk. The main advantage of this model is that allow recognize the risk areas to make appropriate management decisions. However, these models do not give ignition or spreading probabilities. Among these models we can found the studies of Chuvieco and Salas [31,47], Rathaur [48], Neeraj [49], Maselli *et al.* [50] and Roy [24]. In the other hand, the multi-criteria risk analysis also considers expert knowledge into the risk model. However, one of its objectives is to diminish the subjectivity on the selection on weights. This approach is useful when expert's opinions are diverse, helping to make agreements among experts. One example of the use of this method can be found on Chen *et al.* [51]. The statistic models are usually accurate models [52]. They are dependent on the spatial characteristics of the study area and therefore can not be extrapolated to other areas. Among the statistic analysis used to model fire risk are: linear regression, logistic regression and Poisson distribution [31,52-54]. In the same way, neural network is a useful method when the fire patterns are very diverse or when the fire variables are not clear. Other types of models are those

that simulate fire spreading. Some recognized models are the Behave, FARSITE and PYROCART models.

Under these criteria, models can be also divided according its time and spatial scale [5]. The long term studies, takes in account static variables as topography, road network and vegetation type. They show risk patterns and are useful to the development of prevention and management plans. On the other hand, the short term studies use weather data to calculate a daily or weekly risk. Its importance depends on the fire alert that these systems can give in real time. Some examples are the Canadian Forest Fire Danger Rating System (CFFDRS) and the National Fire Danger Rating System (NFDRS) from U.S.A.

#### 1.1.6. Forest fires in Mexico

The occurrence of fires (size, frequency and intensity) have increased significantly world wide in the last decades as an effect of the El Niño periodic phenomenon, deforestation and other causes [55]. During 1998, an El Niño year, Mexico was extremely affected by these events, registering 14,445 fires which affected 919,000 ha, being the most disturbed vegetation type the Pine-Oak forest [11,56,57]. Eight years later, in 2006, this trend continues registering 8,725 fires, which damaged more than 240,000 ha [58]. Michoacán is one of the most fire-affected states, especially in the year 2005 when 17,443 ha were affected [11]. The main cause of fire was human activities in a form of grassland burning for cattle feed and campfires [59].

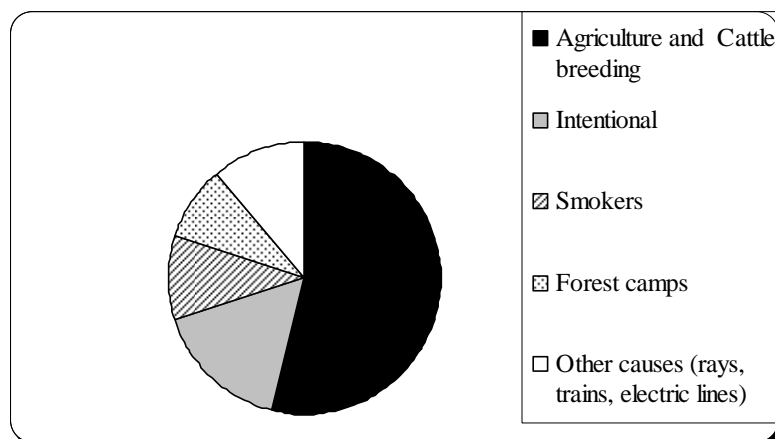


Figure 1-1. Main causes of forest fires in 1998, Mexico

The causes of fire are the result of an interaction between, biophysical and social elements. In Mexico, although, climatologic phenomena like “El Niño” or the dry season increase the frequency and intensity of fires, human activities are still the main cause that provokes them, among these, agriculture is the most frequent fire-prone activity since it represents 48% of the total (Figure 1-1) [60].

The forest fire season is from January to June, being March and May the most fire intensive period [61]. Ninety percent of the fires are superficial, and most of them occur in the dry season caused by human activities [62]. For the centre of the country, where Michoacán state is located, the most important activities that promotes fires are grassland burning for cattle feed and campfires [59]. Although it is true that the natural fires are an important part of the dynamics of the ecosystems, they do not occur with the same frequency as fires caused by human activity.

### **1.1.7. Actual fire combating and prevention in Mexico**

The actions to control and mitigate forest fires in Mexico are carried out by the National Program of Forest Fire Protection. Its target is to increase the prevention actions, detecting fires and reducing the response time and the affected area [58]. Three levels of government, civil organizations and volunteers contribute to the above mentioned activities. These activities are coordinated, since 2002, by the Ministry of Environment and Natural Resources (SEMARNAT) and the National Forest Commission (CONAFOR), which is the responsible institution of carrying out the anti-fire actions in Mexico [63]. At federal level, 18 agencies (13 State Departments and 5 federal dependencies) take part in a coordinated way in this program.

The main actions against fires considered in this program are; prevention, detection and combating. One of the primary actions is the detection of fires. To do this in a comprehensive way the actions are divided into four types [63]:

- Fixed Terrestrial Detection. It is carried out through the use of observation towers installed in forest camps. These towers are located in strategic points from which the staff observes and reports the occurrence of fires.
  
- Mobile Terrestrial Detection. Since there are areas or places where the observation towers are inefficient to detect fires; a different approach is needed to complement to the previous type. To detect the occurrence in such places, this detection is realized by the Fire-Control Brigade patrolling in motorized vehicles, mainly in zones where there are a great visitor's inflow, or where the forest values are high.
  
- Aerial Detection. The use of flights to cover areas where there are no observation towers and roads for the access of ground personnel. However, this is an indirect strategy; given that there is much area to cover, and the agencies in charge of fire control are not able to afford flights in the whole area. Aerial reports are made by the Mexican Air Force, federal agencies, commercial and private airlines, which are required to warn flight controllers of airports once they have spotted a forest fire. The airport authorities in turn, report the fire to the State and National Center for Forest Fire Control.

• Remote Sensing Detection. The National Commission for the Knowledge and Use of the Biodiversity (CONABIO), the Geography Institute of National Autonomous University of Mexico and of the National Meteorological Service (SNM) detect fires by using satellite images of NOAA-AVHRR, MODIS and GOES. The CONABIO receives these images two times a day, whereas the national water commission (CNA) receives the images every 20 minutes. Then, these images are processed to allow the observation of possible fire occurrences using Hotspot Algorithm. The detected hotspots in the previous step can be converted to a map form for the purpose of publication and dissemination. In this case, CONABIO and SNM process the information and publish it in the internet as part of the Hot-Spot detection Program. Both agencies offer real-time interactive fire maps, in which can be observed the vegetation type where the fire happens. Moreover, the Canadian Forest Service produces a meteorological risk map (at a national scale) for the Mexican government. This spatial product reports the forest conditions and also the fire events. This map is updated daily.

## **1.2. Research problem**

Although fires are beneficial for some ecosystems, they cause biological, socio-economical damages, and consequently biological diversity losses [55]. In spite of these Mexican government efforts for fire prevention, they are not very effective to reduce fire frequency and intensity, as every year they tend to increase [56].

The study area is one of the most affected zones in Michoacán state [64]. Nevertheless the risk areas and the important factors influencing fire have not been fully identified yet. The generation of fire risk maps is still lacking for the major part of the country, with a few scanty academic contributions. For this reason it is urgently needed that Mexico, develops with high efficiency, fire prevention strategies, in order to avoid the loss of natural resources. It is necessary to integrate the available information and also generate more detailed information at large and small scale, indicating the causes that favour the beginning and expansion of fires for its possible prevention. A forest fire risk map can help to solve this problem because it shows fire probability in a given place [19]. The fire risk map would be of great value and essential in the management of forest resources for a more suitable response by the local authorities. For this reason the development of a database for fire risk seems to be a high priority project.

Many authors have focused their efforts on the fire risk assessment. The approaches are diverse, depending on the variable and the selected scale. In general, the final product is a prediction index of the fire risk in space and time [65]. Among the variety of fire prediction systems around the world stands out: the Canadian Forest Fire Danger Index (CFFDRS), the National Fire Danger Rating System (NFDRS) and the Joint Research Center (JRC) [65]. Likewise, there are some known programs that simulate forest fires behaviour as Behave, FARSITE, or CSIRO.

Although the fire risk models development in many countries has reached a very advanced level, in Mexico there are few works that evaluate forest fire risk. Most of the studies in Mexico are focused on small areas due to lack of information, especially fuel data. For example, Villers-Ruiz and Lopez-Blanco [66] analyzed the fire risk in the Malinche volcano (706 km<sup>2</sup>) using the BehavePlus program developed by the US Forest Service. To accomplish this objective the fuel was classified according to the density of trees. The results describe which vegetation type has the highest fire dispersion rate. Other case study calculated a fire-risk index for the Chipinque Ecological Park (16.25 km<sup>2</sup>) [67]. The mentioned study used a fuel inventory, an IKONOS image, and land use information to determine fire risk index. The final result was a fire risk map. Both works have focused mainly on the fuel mapping to develop their fire models.

This study follows the approach used by Neeraj and Hussin [49] since it integrates biophysical and human variables. Fire probability depends on the ignition causes and preconditions, while, impact probability is associated with fire behaviour and suppression. Therefore, there are four main factors that modify the probability of a forest fire: 1) fuel, 2) physical environment, 3) causal factors and 4) prevention and suppression [48]. Based on this approach this study will add two new sub-models that will include ignition and weather variables. This integral approach, the use of a meso-scale and a weather multi-temporal sub-model are the main contributions of this study for fire risk modeling in Mexico. This model will not be concern much with fuel mapping. Likewise, it is important to point out that the addition of an ignition sub-model will be crucial to the final forest fire risk model developed in this study, since human activity is the first cause of fires in Mexico.

Consequently, the main goal of this study is to develop a forest fire risk map, using remote sensing and GIS tools and all available data. This work will be focused on developing a method to generate a fire risk map for a Michoacán area based on physical, biological and social factors.

### 1.3. Rationale

Although Mexico is a mega diverse country [68,69], annually loses thousands of hectares of forest due to fires [11] during intentional or accidental fires consequence of the burnt of agriculture fields, grasslands, camping and other activities [57]. For this reason it is necessary to develop a decent strategy that can be used in fire prevention. Combating fire involves a considerable economical support and a huge amount of time, without mentioning the lives on risk to carry out this work. An example of this can be seen in 2003 when 252,882 man days were invested for fighting forest fires [63]. This study tries to contribute to fire prevention by developing a forest fire risk map. The contributions of this study are:

- Detecting burnt forests using medium and high spatial resolution satellite images.
- Analyze biophysical and social factors affecting forest fire in the test area of Michoacán, Mexico.
- Developing a forest fire risk model for the test area of Michoacán, Mexico.
- Supply a forest fire management recommendations for the test area of Michoacán, Mexico based on forest fire risk map.

#### 1.4. Research objectives and questions

The general objective of this study is to model forest fire risk for a critical zone in Michoacán. In order to achieve this, the specific objectives and the research questions were divided in three phases.

<p><b>Exploratory Phase</b></p> <p>1. To detect and map forest burnt areas using a high resolution ASTER image  <b>Q1.</b> Can burnt area be detected using a high resolution ASTER image?</p> <p>2. To analyze the main biophysical factors related to forest fires in the study area  <b>Q2.</b> Which of these factors are more related to fire through its relationship to burnt areas?</p>
<p><b>Modeling phase</b></p> <p>3. To develop a forest fire risk model for the study area in order to identify the fire prone areas.  <b>Q3.</b> Which are the prone fire areas (high, medium and low fire risk) in the study area?</p>
<p><b>Validation phase</b></p> <p>4. To validate the forest fire risk model  <b>Q4.</b> How accurate is the forest fire risk model developed in this study?</p>



## 2. STUDY AREA

The study site is located in Michoacán state (Figure 2-1), one of the areas in Mexico with more forest fires. This state represents 3% of the entire country with 58, 643 km<sup>2</sup> of area and it is divided in 113 municipalities and 10 economical regions [70]. Due to its large area, its complex topography and the altitude range (0-4000 m a. s. l.) the climate varies from dry and hot to temperate and semiarid. Michoacán's vegetation includes Pine, Oak, Pine-Oak and fir forest, cloud forest, dry tropical forest, moist tropical forest, subtropical thicket, scrubland, spine thicket, natural grassland, induced grassland, cultivated grassland, palm tree forest, and mangrove. This is a high biodiverse area. There are more than 985 plant species, 88 mammal species, 460 bird species, 112 reptile species, 36 amphibian species and 38 fish species [71]. Nevertheless, it is among the states with highest deforestation rate in the country. The total number of inhabitants is 3 495 742 from which 113 166 are indigenous [72]. The official language is Spanish; however 12% of the indigenous habitants do not speak it. The most important indigenous groups are Purepecha, Nahuatl, Mixteca, Mazahua and Otomi [72]. These groups are generally characterized by high level of poverty. In accordance with the Index of Human Development calculation for Mexico, Michoacán is one of the states with less development and subsistence level [73].

### 2.1. Location

The selected study area is based on an ASTER image taken at the end of the dry season (May, 2006). The criteria selection of this image was: 1) Geographical location, 2) Temporally coincidence with dry season, 3) Null cloud cover, 4) Medium spatial resolution (15 m), and finally 5) a High frequency of fires. The exact location of the study area is between the coordinates 20.15 -102.5 NE, 19.59, -102.63 SE, 20.07, -101.92, NW, 19.51, -102.5 SW. The area of this test site is 3942 km<sup>2</sup>, which includes 23 municipalities of Tepalcatepec, Lerma-Chapala, Purepecha and Bajío regions (Figure 2-1). Its highest point is 3400 m, and its lower point is 1110 m.

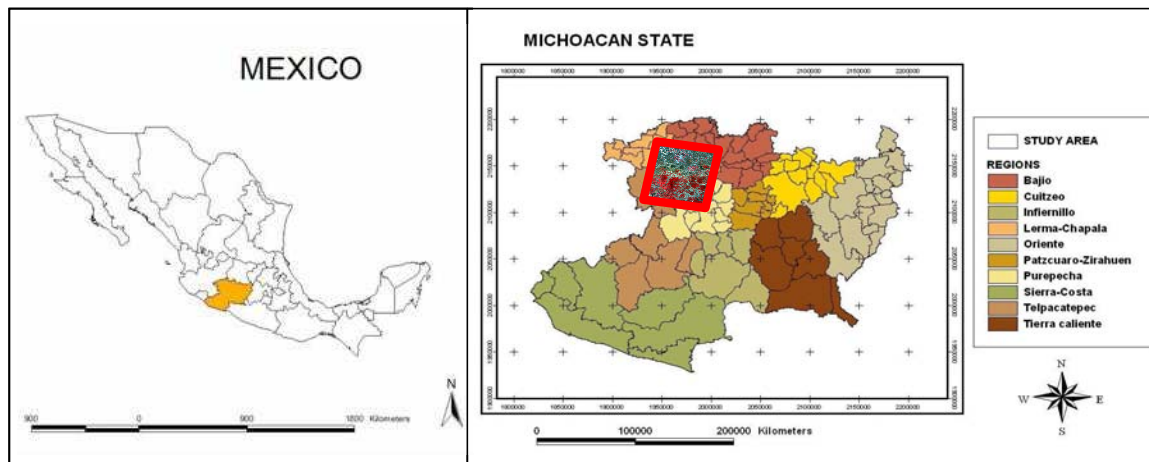


Figure 2-1 Study area localization in an ASTER image of Michoacán, Mexico

## 2.2. Climate

Due to the altitudinal difference there are two general climates subtropical and temperate. The average temperature and rainfall values of the warm and the template areas can be seen in Figure 2-2.

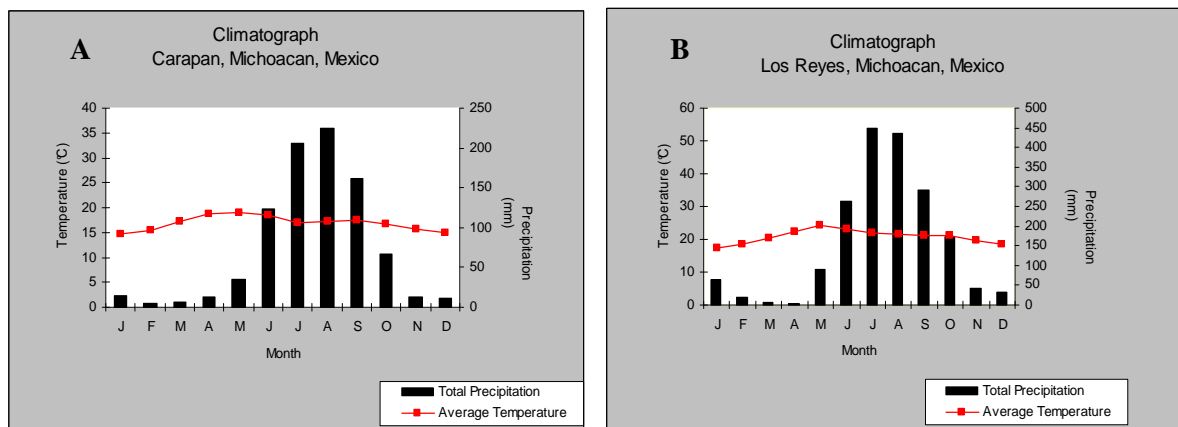


Figure 2-2. Climatographs from (A) Los Reyes station (subtropical) and (B) Carapan station (temperate) in Michoacán, Mexico

## 2.3. Vegetation

There are 7 types of vegetation distributed in the whole area: Pine forest (17.1%), mixed Pine-Oak forest (13.8%), secondary scrubland (11.5%), grassland (9.8%), Oak forest (7.1%), dry tropical forest (1.2%), and hygrophilous vegetation (0.1%). This area also includes a National Park named “Parque Nacional Lago de Camecuaro” in Tangancicuaro municipality. In the

following paragraphs is described each type according to Rezdowski (1978) and Labat (1995) floristic studies. This information will be very useful later in the creation of the fuel risk model

**Pine forest.** The Pine forest is one of the most representative vegetation communities of Mexico. Usually it is found in climate with temperature range of 10-20°C and 600-1000 mm of total annual precipitation. This geographic distribution is related to the presence of mountains and high elevation topography. In the west of Michoacán state, Labat (1995) classified the Pine forests using the species temperature preference. These categories are termophilous and mesophilous forests. The termophilous Pine forests are located in the Sierra Tarasca between 1400 and 2100 m a. s. l., over extrusive Igneous Rocks and Andosols. The Pine trees of these forests are from 15 to 20 m height, but it is possible to find trees of 25 m. The tree canopy percentage is from 60 al 80% and the trees mean density is about 692-860 tree/ha, with diameters no higher than 70 cm. The dominant species for this termophilous forest are: *Pinus oocarpa* (493.3 trees/ha), *P. douglasiana* (173.3 trees/ha), *P. michoacana* var. *corneta*, *P. ayacahuite* var. *veitchii* and *Pinus pringley*. However there are many other associated pine species present. One particular case is *P. oocarpa*, which is adapted to fires.

The Mesic Pine forest is located in more humid zones between 2600 and 2700 m a. s. l over basaltic extrusive rock. Here the dominant species are: *P. montezumae* (45.2 trees/ha) and *P. pseudostrobus* (84 tree/ha), *P. teocote* (63.2 tree/ha). In the highest zones dominates *P. leiophylla* (181.2 tree/ha) and in the lower zones (2500) the mesophilous species are mixed with the termophilous Pine forest. In this part it is usual to find it mixed with Oak and *Alnus* species. The height of the trees is from 15 to 25 m, whereas the tree mean density is 615 tree/ha with diameters of 5-100 cm. According to Rezdowski, this forest shows a lot of fire evidences. Other kinds of disturbances present in these areas are: illegal cutting, resin extraction, land use change to agriculture.

High percent of Mexican Pine forests are under demographic pressure. This type of forest is cut and used for several purposes, from wood and pulp for paper making to land use change for agriculture and cattle breeding. In general from the mentioned activities, is important to highlight that agricultural and cattle breeding have a great influence on Pine forest. The use of fire is a common practice in agriculture whereas the burning of grassland is used constantly to renew the grass for the cattle. As a result, this forest shows intensive human disturbance and frequent fires. It is calculated that 80 percent of the forest is affected by fires. Nevertheless, it is not clearly known if fire is part of the Mexican Pine ecosystem dynamic. As Rzedowski mention, the forest response to a fire depends on its species composition. The presence of serotinous cones of some species as *Pinus oocarpa* shows that some Pines are resistant and favoured by fire. Other species as *Pinus patula* (which have serotinous cones too) are indirectly related with fires since they are commonly found in disturbed forests. Finally other Pine species, more sensitive to fire, cannot recover after a fire incidence. In this situation, fire contributes to the lost of forest areas. Moreover, in the case of the herbaceous stratum, the main family in this forest, the Gramineae, is

favoured by fire. In some cases this fact leads to a positive forest fire feedback since grass presence induces or favours fires.

**Oak forest.** The Oak forests are characterizing Mexican mountainous areas. They are found in climates from temperate to subtropical with temperatures of 10 to 20°C and 350-2000 mm of annual precipitation. In the subtropical climate Oaks appear as a scrubland. According with the floristic study of Labat, the Oaks in this area of Michoacán are distributed between 1950-2300 m a. s. l. However, they can also be found up to 2400 m a. s. l. In its highest distribution they are close or mixed with the mesophilous Pine forest. In addition, the Oak forests grow on soils derived from Andesite and Basaltic rocks.

The Oak forest is one of the high diversity communities in Mexico since there are more than 150 species of Oaks. This implies an enormous floristic, physiognomic and ecologic diversity. We can find two types of vertical structure in this forest, one from 10-15 m and the other from 4-9 m. This difference is reflected also in the two tree diameter classes (55-75 and 20-55 cm). In the Oak forest trees density is of 2160 tree/ha (5075-280 trees/ha), with dominant tree species: *Quercus sideroxyla* (378.4 trees/ha), *Q. obtusata* (399.6 trees/ha), *Q. deserticola* (497.5 trees/ha), *Q. subspathulata* (289.3 trees/ha), *Q. castanea* (275.6 trees/ha) and *Quercus laeta* (132.5 trees/ha). The Oaks are deciduous; however the leaf off period is very short during the year (less than a month). Even some species never lose their leaves. The herbaceous stratum depends on the density of the forest. It is composed mainly of grasses and plants from the family Compositae, but also includes a great diversity of other families. Moreover, other kind of trees that can be found in these forests as *Arbutus*, *Cercocarpus*, *Crataegus*, *Cupressus*, *Juglans*, *Juniperus*, *Pinus* and *Pseudotsuga*.

As a result of its low height and thin logs, the Oak forests are more used locally than industrially. Its use is restricted to furniture and post construction, handcrafting or fuel. In the same way as the Pine forest, they are affected by the land use change, mainly to agriculture fields and grasslands for cattle. Fires are a common practice in the driest and hottest months. This fact leads to changes in the composition and the structure of the forest, and finally to its disappearance. It is worth noting that Oak trees have a slow growth. This process in a long term produces a shift in which Oak forest is converted to a scrubland or grassland; both are more useful for cattle breeding. After that the ecological and hydrological consequences are severe, observing high rates of erosion. The presence of regular fires favours the growth of *Eysenhardtia polystachya*.

**Mixed Pine-Oak forest.** Since both genera grow in similar environment, this type of vegetation is composed by a mix of Pine and Oaks distributed in different percentages. The Pine-Oak forest is considered as a separate vegetation type because its distribution is as wide as the pure Pine or Oak forest. Consequently, the coincidence of both species is not necessarily seen as a transition. This community is an evergreen forest, given that pines never lose their leaves.

**Tropical deciduous forest.** This vegetation is typically found in subtropical climate (temperature of 20-29°C) located in areas of altitudes of among 0-1900 m a. s. l. The mean annual precipitation is from 600-1200 mm. But should be noted that there are two major seasons: dry and wet. Therefore, this vegetation type is characterized by its dominant tree species, which lose their leaves in the dry season of the year (5-8 months). In addition it is usually found in thin and rocky soils of the slope of the hills.

The preserved forest has a high density of trees between 5 and 15 m of height and 50 cm of diameter. In Michoacán state the original vegetation is disappearing. As this type of vegetation is affected by agriculture, cattle breeding, forest fires, and selects illegal logging. Therefore, the height of the trees of Michoacán's tropical deciduous forests is not more than 4 to 6-7 m with diameters of 15-30 cm. The family Leguminosae is dominant in the tree stratum, but the genus *Bursera* is a common one. Moreover, it consists of cacti species, plants from the genus *Beaucarnea* and *Yucca* and other shrub species. The most important tree species are: *Acacia pennatula* (178 trees/ha), *Heliocarpus terebinthaceus* (128 trees/ha), *Ipomoea murucoides* (62 trees/ha), *Bursera cuneata* (84 trees/ha), *Zanthoxylum affine* (76 trees/ha), *Eysenhardtia polystachya* (54 trees/ha), *Opuntia cochinera* (20 trees/ha), *Manihot caudata* (42 trees/ha), *Lysiloma mycophyllum* (46 trees/ha), *Mimosa rhodocarpa* (50 tree/sha), *Euphorbia fulva* (20 tree/sha) and *Opuntia chavenia* (16 tree/ha).

**Secondary scrubland.** The tropical deciduous forest is one of the vegetation communities most affected in Mexico. Areas covered by this vegetation type are used for agriculture. However, they are abandoned quickly because the scarce soil and high percent of rocks are typical characteristics of the areas where this forest grows. Its regeneration just occurs in the absence of disturbance. Hence, disturbance takes place by cattle, fires and selective cutting; thus tropical deciduous forest is converted to a permanent scrubland. In the composition of this scrubland remains many of the species of tropical forest. Among the most frequent species are: *Acacia spp.*, *Heliocarpus terebinthaceus*, *Ipomoea murucoides*, *Bursera spp.* and *Erithrina spp.* species. In the dry season the remnant of cacti characterize the appearance to the area.

**Grassland.** All the grasslands located in this area are cultivated or induced for cattle breeding. The grasslands areas take the place of the other types of vegetations cited above. For its maintenance fire is frequently used as a method of grass renewal. When grassland is established, the original vegetation cover hardly comes back due to the frequent use of fire and the presence of grazers. However, if these areas are abandoned, the vegetation starts an ecological succession process within the intermediate vegetation which is the scrubland. Grasslands derived from Pine or Oak forests are dominated by genera like *Andropogon*, *Aristida*, *Boutelova*, *Bromus*, *Deschampsia*, *Hilaria*, *Muhlenbergia*, *Stipa*, *Trachypogon* and *Trisetum*.

## 2.4. Land use

The main land uses are seasonal agriculture (23%), irrigation agriculture (6.2%), and livestock farming (9.8% of grasslands). The percentage of these activities varies according to the municipality. In the general agriculture is the most important economical activity in the study area. Some of the crops that grow here are: corn, beans, wheat, chickpeas, broad beans, sorghum, lentil, alfalfa, oat, sugarcane, tomatoes, strawberries, cucumbers, zucchinis, pears, peaches, plums, limes, avocados, chilli peppers, onions, potatoes, blackberries, apples, guavas and coffee beans [74]. Grasslands are mainly used for livestock farming. The livestock farming mainly include the care and breeding of cows, pigs, chickens and sheep [74]. The industry is not very developed in all the municipalities. However, Uruapan municipality is among the most industrial developed municipalities of Michoacán state. Finally, it is worth to mention that there are forestry activities in this area. The degree of intensity of these activities also varies according to the municipality. For example in the municipalities of Tocuambo, Los Reyes, Uruapan, Cheran and Charapan forestry is the main activity [74]. In other municipalities forestry is carried out in lesser degree. In Mexico, particularly in the State of Michoacán, the deforestation due to illegal logging is the main activity on forests land. Bocco et al. [75] report that Michoacán temperate and tropical forests lose every year about 1.8% and 1% of its area, respectively. Of particular interest in this study is the analysis of deforestation rate per municipality. For example, the municipality of Churintzio, located in the north-western of the study area, had a forest coverage lost of 12.8% between 1975 and 1993. According to the same study the municipalities of Jacona, Villamar and Tocuambo lost their forest cover in the same period of time. This fact highlights the seriousness of the problem in the area. The main activity that contributes to the deforestation is the illegal logging. However, forest fires also contribute to the loss of forest coverage. Moreover, natural burned areas does not recover and are clandestinely occupied for agriculture, fruticulture and pasture [57,76]. In the Meseta Purepecha the forest decrease is caused mainly by the establishment of new avocado (*Persea spp.*) orchards [57]. México is the world first avocado producer and Michoacán state produces 85% of the national production generating 690,000\$ per year. This situation strengthens the economic incentive for converting forests to avocado orchards [76]. The main avocado producer municipalities in Michoacán state are: Uruapan (15,373 ha), Tancítaro (14,122 ha), Peribán (12,779 ha), Tingüindin (3,630 ha), Los Reyes (2,692 ha).

## 2.5. Population

Over the study site are 426 settlements, from which the most important are Zamora de Hidalgo, Jacona de Plancarte, Los Reyes de Salgado, Paracho de Verduzco, Tangacicuaro de Arista, Purepero de Echaiz, Santiago Tangamandapio, Ario de Rayon, Tarecuato y Capacuaro. All the settlements located in the Meseta Purepecha have indigenous population, from which a great part suffers economic poverty.

## **3. METHOD**

Modeling forest-fire risk is an important tool for the prevention of disasters. Throughout this work I intend to develop a fire risk model and then produce a forest fire risk map for the study area in the state of Michoacán. The production of this map will be the result of a research focused on three main phases: 1) Exploratory, 2) Modeling and 3) Validation. The methodology for each phase will be explained in the following paragraphs.

### **3.1. Exploratory phase**

#### **3.1.1. Literature review and selecting factors influencing forest fire**

The first phase consisted of review of literatures on the forest-fires and available databases in order to obtain actual information related to previous studies on forest-fire, data records and a list of the institutions (both, local and federal) in charge of the fire monitoring and prevention, and their strategies for fire-prevention. This review will provide a better knowledge of the main factors affecting forest fire and helped on the factor selection. As it was mentioned in the introduction, the variables that influence the beginning of a forest fire and its development are: 1. fuel availability, 2. weather, 3. topography and 4. human activities. These factors integrated in the GIS model were: vegetation type, temperature and precipitation, elevation, slope and aspect, and land-use, road network and habitation data.

During this phase, a new fire-event database was built for the study purposes using COFOM records and MODIS hot spots from 2003 to 2006 and 2004-2006 respectively.

#### **3.1.2. Data processing**

MODIS hot spot data were obtained from CONABIO, while the ASTER image was downloaded from the Earth Observing System Gateway website (<http://edcimswww.cr.usgs.gov/pub/ims/welcome/>). The ASTER image was geometrically corrected using ILWIS ver. 3.31 relating georeference tie points of the image with a topographic map scale 1:50,000. The transformation used for the geometrical correction was the Affine method [77]. The root mean square error (rmse) of the georeference was  $\pm 0.66$  mm due to the quality of the topographic map. According to the Ilwis Reference Guide [78], “The value of Sigma (in millimetres) for the current data indicates the accuracy with which the control points have been digitized. If the value of sigma is much larger than 1, this indicates that an error was made when digitizing the points or

when entering the coordinates. Sigma is the standard deviation calculated from the difference between the digitized and the calculated control points”.

The thematic maps of land cover, roads and hydrology of scale 1:250,000 and topographic map of scale 1:50,000 were used in this study. All the thematic maps were obtained from INEGI digital database. From each attribute, six maps were used and mosaic in order to cover the complete study area. Likewise, the fire ground records and fire headquarters location were obtained from CONAFOR and COFOM databases. All maps were converted to the Alberts Conical Area projection.

The Digital Elevation Model (DEM) was derived by interpolation of contour lines (every 20 m) from the topographic map. The aspect and the slope map were calculated from the DEM. Nevertheless, due to missing data in mosaicing two topographic sheets and to avoid false information, it was necessary to apply a 5 x 5 majority filter on those maps (for more information on this process refer to [77]).

### **3.1.3. Study area demarcation**

The demarcation of the study area was made on the basis of the of the ASTER image that fulfilled the following premises: 1) To be an area with a high frequency of fires, 2) to be composed in its majority of natural vegetation, and 3) that possess (within possible) a representation of the majority of Michoacán state’s diversity; this means: an area that includes most common vegetation types found in the state.

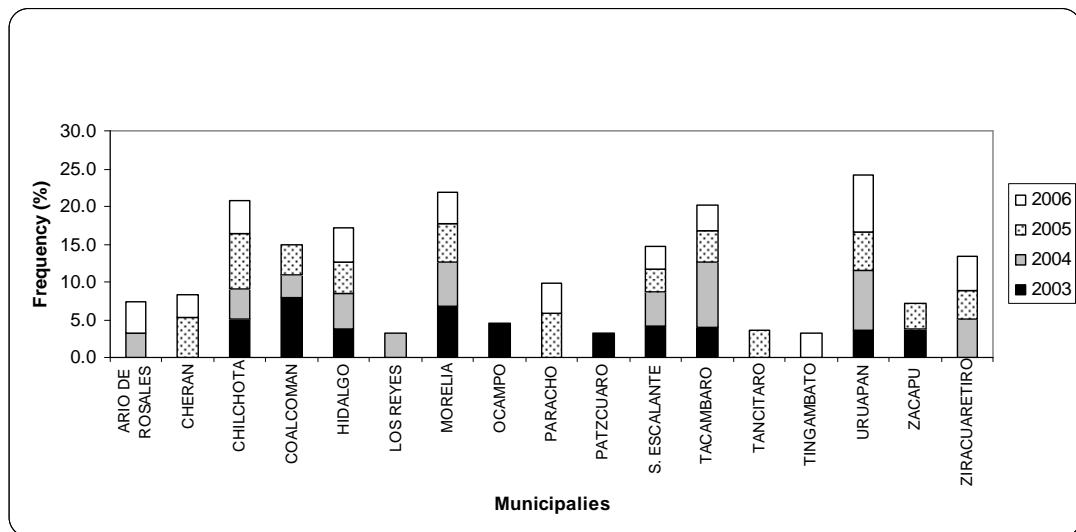
In order to detect which areas in Michoacán state are the most affected by forest fires (i. e. condition 1), CONABIO’s MODIS hot spots and COFOM’s ground records were used. Hot spots are detected by remote sensing while ground records are points taken after a fire is spotted and extinguished. Both information sources come from governmental institutions. More over, the COFOM records are part of the official report of forest fire in the state of Michoacán and are continuously published in the newspapers as these areas with more forest fires incidence. CONABIO hot spots, are used to warn foresters about the fires in the country. These two sources complemented each other and allowed us to visualize which areas are more frequently burned. However, since both databases come from a different source; there were some differences among the COFOM fire frequency reports and MODIS hot spots. While the COFOM’s report shows Oriente, Bajío and Cuitzeo as the most forest fire affected regions, hot spot data indicates that Sierra-Costa, Telpacatepec and Tierra Caliente are the regions with the most high frequency of fires (Table 3-1).



**Table 3-1 Comparison between COFOM reports and MODIS Hot spot**

Fires	COFOM report	Hot spot day	Hot spot night	
-	Sierra-Costa	Patzcuaro-Zirahuen	Patzcuaro-Zirahuen	
↓	Infiernillo	Cuitzeo	<b>Lerma-Chapala</b>	
	Tierra caliente	<b>Purepecha</b>	<b>Bajio</b>	
	Patzcuaro-Zirahuen	<b>Lerma-Chapala</b>	Cuitzeo	
	<b>Tepalcatepec</b>	Infiernillo	Infiernillo	
	<b>Lerma-Chapala</b>	<b>Bajio</b>	<b>Purepecha</b>	
	<b>Purepecha</b>	Oriente	Oriente	
	Cuitzeo	Tierra caliente	<b>Tepalcatepec</b>	
	<b>Bajio</b>	<b>Tepalcatepec</b>	Tierra caliente	
	+	Oriente	Sierra-Costa	Sierra-Costa

There are many reasons that could explain the differences between these two sources. The efficiency of COFOM brigades were not the same in all the municipalities or could be biased to more populated areas with easy access. Other explanation could be that reliability of MODIS data for Michoacán is not known. Also it is probable that the forest fires indicated by MODIS hot spots are agriculture fires which are not attended by the fire brigades. Nevertheless, it is not possible to determine the origin of these differences analyzing the available data in this study. In spite of this, the data give an overview of the municipalities most affected by forest fire. For example, the Purepecha region is one of the most affected regions as it shows the COFOM reports [64] and newspaper news [79,80]. The COFOM reports allows knowing which are the regions and municipalities with more forest fires in the state. The municipalities with more fires according to this source are Morelia, Tacambaro, Chilchota and Uruapan (Figure 3-1). The Tepalcatepec region also coincides with the MODIS hot-spot most fire affected regions (Table 3-1).



**Figure 3-1. Michoacán's municipalities with highest percentage of forest fires in four years (COFOM)**

#### **3.1.4. Vegetation type map improvement**

To fulfil conditions 2 and 3 (natural vegetation, and to represent Michoacán state's diversity), the National Forest Inventory map at scale 1:250,000 was used. This map organizes information in four hierarchic levels, from the most general to particular data are: Formation, Type, Community and Sub-community. The reliability of this map for the Formation level is of 70% or more [81]. However, as mentioned by Velázquez et al. [35], at a larger scale and lesser level aggregation in the legend, the probability of making a mistake increases. Moreover, the minimum mapping unit of this map is 1 km<sup>2</sup>. Thus, the use of this information at a more detailed level must be done carefully. In this study the level of community was employed, consequently, it was necessary to improve the quality and detail of this Forest Inventory map. Therefore, the polygons of the map were revised and they were corrected digitally by overlaying with the ASTER image. Finally, a field trip was carried out to corroborate those areas in where the vegetation type assignation was unclear. As this map also includes the land use, as agriculture fields, grasslands and cities in the future it will be called Land cover map. Land cover map is shown in Appendix 5.3.

#### **3.1.5. Burnt area mapping**

Once the study area was defined, a burnt area map was created. For this purpose an ASTER image was used, since such image is reported in the literature that it is useful for mapping historical or recent fires. Their high resolution and multispectral bands in the visible light, near infrared, shortwave infrared and thermal infrared wavelength [29], allow many compositions used to identify fire scars. In this study the bands 2, 3, 1 in red, green and blue were used, since it is a known composition that highlights burn scars well [36]. Given that the chosen image belongs to the final days of the dry season (January to June) it was possible to identify and map digitally the burnt scars. Non forested areas were mask in the mapping. Furthermore, MODIS data and ground records of four consecutive years (2003- 2006) were available for additional information.

#### **3.1.6. Analysis of factors influencing forest fires**

In this phase, factors effecting forest fire factors were analyzed (Figure 3-2). All the burnt areas were related with an attribute map to visualize the relationship among them. Crossing burnt area map with all available maps lead us to understand which are the main factors and their classes that promotes fires. For the analysis of mentioned factors, variance homogeneity was determined (Bartlett's test), and then the ANOVA test was applied. A Tukey test was applied to see difference among variables. In the case of lack of variance homogeneity, data were analyzed by the Kruskal-Wallis test. The means were compared visually using box-and-whiskers plots at a significance of 0.05 [82]. These factors were used to have a better understanding of the final forest fire risk model.

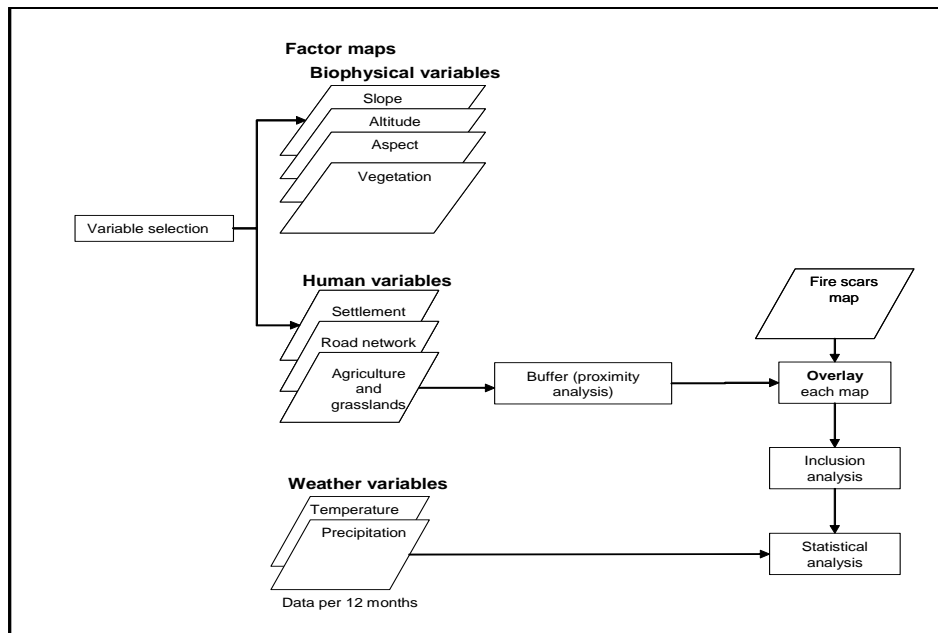


Figure 3-2 Factor Analysis

### 3.2. Modeling phase

In order to know the forest fire risk for the study area, in the second phase, all the factors analyzed in the previous phase were introduced in a five step model. Every step (or sub-model) emphasizes the most important factors related with the forest fires. These sub-models are: Fuel risk, Ignition risk, Weather risk, Detection and Response.

In order to model fire risk, the sub-models variables were divided in static and weather. The first 4 sub-models are composed of static variables but since fire behaviour varies along the year depending on climatic conditions, the fifth sub-model is multi-temporal.

The construction of the sub-models was based on the maps of the factors selected in the exploratory phase. The analysis of the spatial properties such as proximity, adjacency, direction, inclusion and exposition, helps to facilitate the modeling phase since it allows evaluate the spatial relationship between the variable and the fire event. In order to determine the categories with more fire incidence, a risk map from each variable was created using logical indices based on the literature review. In most of the cases the maps were reclassified with the index in classes according with the histogram or distribution of the data. In summary, all sub-models were combined by the adding each individual fire risk map. The sum of all sub-models will make the final Fire Risk Map for the study area. The following sections describe each sub-model and the creation of the indices.

### 3.2.1. Fuel risk sub-model

Fuel is one of the main variables that determine fire's occurrence and spread. Without fuel, a fire cannot occur. Therefore, the probability of a forest fire is determined in its majority by fuel quality and quantity [12, 13]. For these reasons fuel must be incorporated in the fire risk model. In order to build this sub-model, topographic and land cover information were used (Figure 3-3). The input maps for this model were: Slope, Altitude, Aspect and Land cover. All the factor maps were reclassified using indices.

This led to individual risk maps which finally were merged to obtain the Fuel risk sub-model. In the final sum, the land cover index was multiplied for 3, since this is the essential element for fire. To add the topographic factor to the fuel-submodel, the sum of aspect, elevation and slope was multiplied for 2. The indices of each factor were based on an extensive literature review and the particular characteristics of the study area. In order to give a general panorama to the reader the next section is focused on the factors description and its relationship with forest fires.

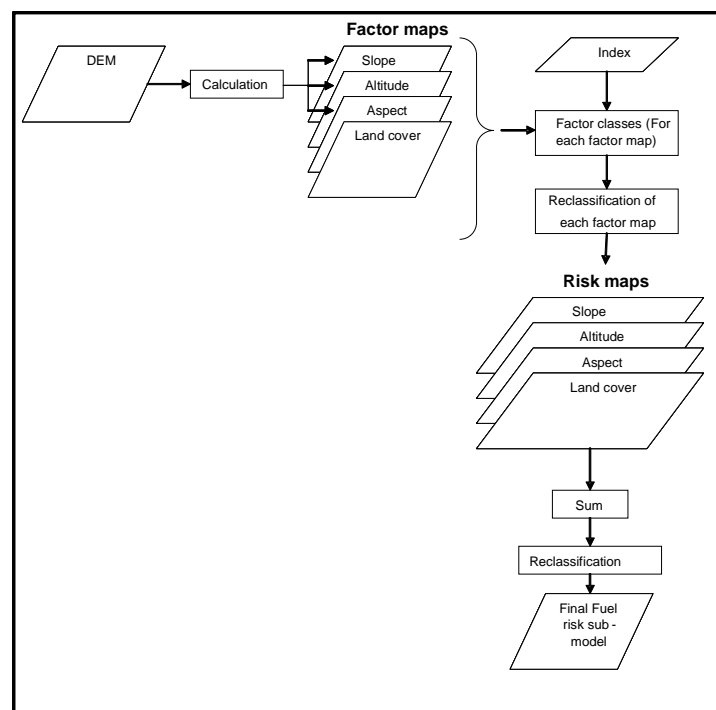


Figure 3-3. Fuel risk sub-model

### 3.2.1.1. Land cover index

The vegetation ranking was made according to the vegetation type characteristics. Table 3-2 shows the variables that were taken into account to generate this index (such as density and biomass). Also it shows the results of a workshop organized by CONABIO, where a group of experts ranked the vegetation depending on the probability of a fire and the recoverability of the vegetation. The Pine forest was ranked with high risk based on its fuel biomass, height and tree density. In addition, other features like flammability were considered in this ranking; for instance pine wood and resins are highly flammable [83]. Furthermore, tropical deciduous forest has the highest rank, since in the dry season this vegetation type presents many fine dry fuels (e.g. leaves and twigs) that favour an easy ignition in the appropriate hot weather. Moreover, this vegetation type has a low post-fire recoverability [84]. On the other hand, in the study area scrublands are secondary vegetation that are highly resistance to disturbance and have a high degree of recovery. Finally, Oak forests were considered as middle risk vegetation type, because of its considerable amount of biomass, but they do not have the density and flammability that the Pine forest has.



**Table 3-2. Characteristics of land cover types and index rating.**

Land cover	Vegetation type		Tree height (m)	Tree diameter (cm)	Tree density (ind/ha)	Mean above ground Biomass (MgC/ha) <sup>a</sup>			CONABIO Susceptibility category <sup>c</sup>	Land cover index
	Pine forest	Termophilous Mesophilous				Tree	Herb	Shrub		
Forest		Termophilous	15-20	< 70	692-860	100.5 ± 10.4	0.15 ± 0.03	0.16 ± 0.03	4	5
		Mesophilous	15-25	5-10	615					
Forest		Oak forest	10-15 and 4-9	55-75 and 20-55	2160	112.8 ± 61.2	0.3 ± 0.1	0.31 ± 0.1	3	3
Forest		Mixed Pine-Oak forest	Intermediate between Pine and Oak forest	Intermediate between Pine and Oak forest	Intermediate between Pine and Oak forest	91.5 ± 8.9	0.1 ± 0.03	0.31 ± 0.03	3-4	4
Forest		Tropical deciduous forest <sup>b</sup>	4-7	15-30	178 (Acacia)	13.6*	n.a.	n.a.	5	6
Forest		Scrubland				28.7 ± 24.8	2.3 ± 0.42	1.7 ± 0.4	2	2
Forest		Plantation	n.a	n.a	n.a	50.5 ± 11.9	0.04 ± 0.01	0.06 ± 0.01		3
Grassland		Induced grassland	Without	Without	Without	Without	0.09 ± 0.08	0.14 ± 0.1	1	1
Grassland		Cultivated grassland	Without	Without	Without	Without	0.09 ± 0.08	Without	1	1
Agriculture			Without	Without	Without	Without	0.10 ± 0.09	0.21 ± 0.2	1	1
Urban									1	1
Water body and rivers									1	1
Bare soil									1	1

a : Source Labat [85]; b: Maas *et al.* [86] c: CONABIO [84]. fire susceptibility categories: 1) Null, 2) Low probability of fires with high recover, 3) Low probability of fires with low recover, 4) High probability of fire with high recover, 5) High probability of fire with low recover.

### 3.2.1.2. Slope index

The slope has a direct relation with fire spread. Fuel exposition is greater as the slope steepness is increased (Figure 3-4) [87]. The fact is that fires spreads quicker up slope than in flat areas. According to McArthur ([88] cited in [5]) the steep of the slope will increase significantly the spreading of a fire; for instance a slope of 10° will double fire spread rate and a slope of 20° will quadruple it. When present, wind is the main element that modifies the contact of the flame with the fuel surface. Hence, fire spread depends on both slope and the wind force and direction [5,87,89,90]. Nevertheless, in absence of wind, slope is the main factor effecting fire spread. Having said that, a slope index was rated as it is shown in Table 3-3. The slope fire risk index is higher in steep slopes than in flat terrain.

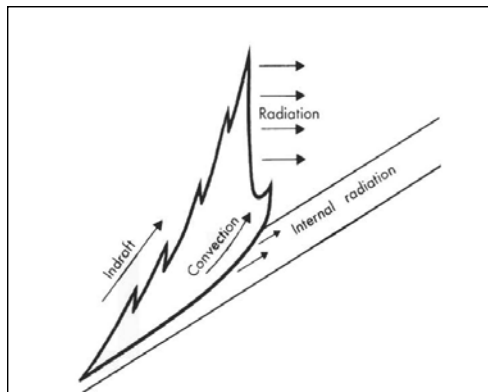


Figure 3-4. Schematic of a fire on a slope.  
Taken from Burgan [1]

Table 3-3. Slope index

Slope class (degree)	Index
0-3	1
3-15	2
15-30	3
30-90	4

### 3.2.1.3. Elevation index

Vegetation type, temperature and humidity are correlated with altitude [91]. Higher areas are more humid and cooler than lower ones. Due to this geographical condition, vegetation types changes with altitude. In the study area, for example Pine forest distribution is limited to highest zones while grasslands, tropical deciduous forest and scrubland are found in lower altitudes. The elevation index relates this information with forest fires, since high temperatures, low humidity and fuel quantity and quality increases the chance of ignition. Elevation indices are showed in Table 3-4.

Table 3-4. Elevation index

Elevation class	Index	Elevation class	Index
1050-1250	3	2250-2450	5
1250-1450	3	2450-2850	4
1450-1850	4	2850-3050	3
1850-2050	6	3050-3250	2
2050-2250	5	3250-3500	1



#### 3.2.1.4. Aspect index

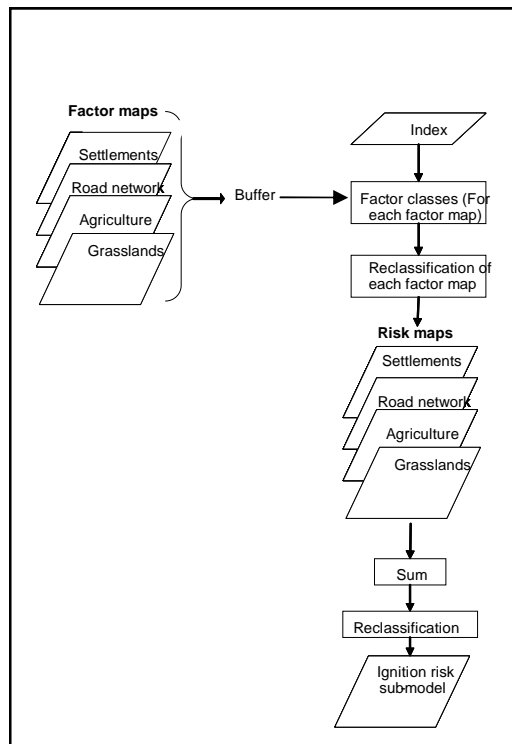
Soil humidity and vegetation distribution are influenced by slope aspect [91-93]. In the Northern Hemisphere the south slope receives more sun hours than the northern aspect, making it hotter [92,94]. This produce a drier condition that is also responsible for differences on vegetation distribution [91-93]. For instance, the vegetation more adapted to dry conditions, as some grasses and Pine species, are favoured in southern slopes [91]. On the other hand, eastern aspect is longer exposed to the sun therefore, receives more time the perpendicular rays of the sun. Hence the fuels located in south and eastern aspects are more prone to get burnt. Table 3-5 shows the aspect risk indices associated to each aspect.

**Table 3-5. Aspect index**

<b>Aspect class</b>	<b>Index</b>
N-NE	2
NE-E	1
E-SE	3
SE-S	4
S-SW	5
SW-W	6
W-NW	2
NW-N	1

#### 3.2.2. Ignition risk sub-model

As it was mentioned before, humans cause more than 90% of fires in Mexico [11,62]. In this model the human activities that can cause a fire in Michoacán state were included. These are agricultural burns and grassland burns (Figure 3-5). From January to May the burnt of grasses and some agricultural practices are carried on, these activities coincide with the dry season. As a result, the forest fire season occurs mainly in the first half of the year. The expansion of fires from these particular areas to forest covers is common. Also the closeness to roads and settlements could be a factor that promotes fires. In fact, it has been proved that there is an edge effect of roads in the forest. Changes like; increase of temperature and light, occurs as an effect of a decrease of the forest cover [95]. Near the roads, the composition of species is different from the original too; exotic and/or invasive plants, many of them pyrophilum, can be found in the borders of highways.



**Figure 3-5. Ignition risk submodel**

Keeping this into account, the data to be considered in the development of this sub-model will be maps of distance to 1) roads, 2) settlements, 3) agriculture fields and 4) grasslands. The distance category it is based on Hernandez-Leal [53] proximity to road categories. These maps were reclassified and rated by a risk index value (Table 3-6). Finally the maps were combined and resulted the final ignition risk map.

**Table 3-6 Distance to roads, agriculture fields and grasslands indices**

Distance class	Risk value
0-15	7.0
15-50	6.0
50-100	5.0
100-500	4.0
500-2000	3.0
2000-5000	2.0
5000-100000	1.0

### 3.2.3. Fire detection risk sub-model.

This sub-model considers the visibility of a fire from forest towers, settlements and roads (Figure 3-6). For this purpose, a viewshed analysis was carried out using the extension 3D Analyst from the program ArcGIS 9.2.[77] and exported to Ilwis 3.1. A viewshed analysis is a complex calculation that

takes into account the DEM information and view point location to determine the visibility taking account the offset, azimuth, vertical angle and radius [96]. In this case, in order to improve the visibility model, the mean vegetation height was overlaid to the DEM (See Table 3-2). This analysis can be performed from points or lines. The calculation from lines is made for each vertex of the line [97]. However, due to the complexity of the road map it was necessary to convert the road map into a point map. Each point was located every one kilometer over the road line.

In order to calculate the visibility, a 5 km threshold, or radius, from roads and/or forest towers; and one of 6 km from the centre of cities were used. However, it is worth to mention that the forest towers used in this study are located in the boundary of the study area and not inside it. Once the overall visibility was calculated, the hidden areas were considered of more risk; since the fires started in this zone can cause more damage to the forests. Visible areas have less risk, because they will be detected and stopped faster. Detection risk indices can be seen in Table 3-7.

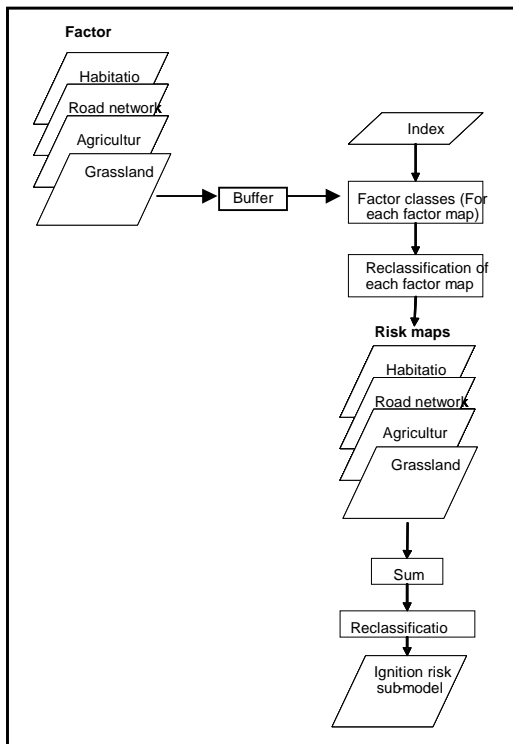


Figure 3-6 Detection risk sub-model

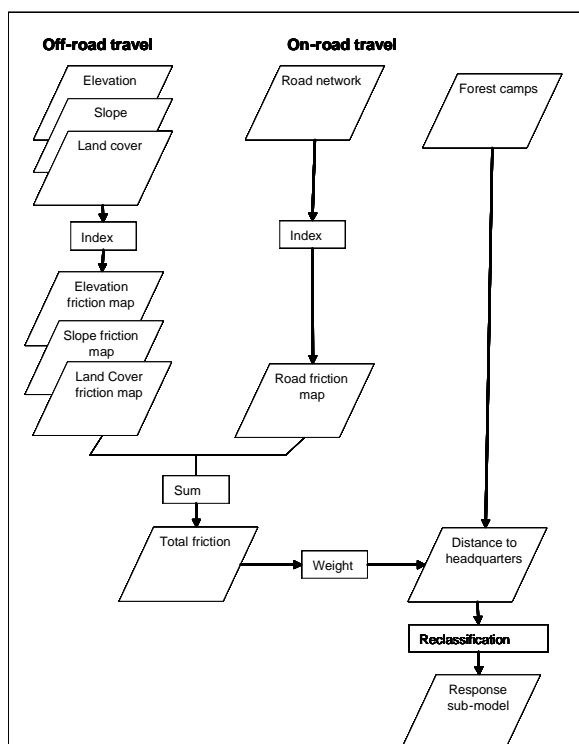
Table 3-7. Detection risk index

Detection class	Detection risk index
Visible	1
Invisible	3

### 3.2.4. Response risk sub-model

Once the fire has been detected and announced, foresters and fire-fighters have to move to stop the fire. The response to a fire is the time between ignition and extinguishment. In this case, the fire response will be considered as the fire suppression force reaction time to a specific fire event anywhere in the area. This response is in a function of the speed of reaction divided by the distance to fire (i. e. everywhere). It is simple and direct to measure the time of on and off-road travel. However off-road travel can be more complex and indirect to measure. Thus for measuring off-road travel time

DEM, land cover and the road network was used to create a friction map that allow us to know the response reaction time for a fire (Figure 3-7).



**Figure 3-7 Response risk sub-model**

### 3.2.4.1. On-road response

For the initial response, fire-fighters usually approach to fire by car; therefore, roads play a key role in the response time. In the study area roads are classified depending on the type of transport supported. The on-road travel was calculated using this road classes (Table 3-8). Time travel response depends on velocity. In this way, the quality of the road is very important. Highways are paved roads designed to drive at higher speeds than urban roads, unpaved roads and paths. Urban roads are narrower and usually present more traffic than highways. Conversely, unpaved roads and paths have a more local use, and its maintenance is less frequent than the more transited roads, though paths can be transited by cars. Particularly for unpaved roads, it is difficult to drive at high velocities. Finally footpaths are paths where the vegetation have been removed and are just used by people and animals.

**Table 3-8 On-Road response index**

Road type	Characteristic	Index
Highway	4-2 lanes	1
Street	Urban road, 1-2 lanes	2
Unpaved road	2 lanes	3
Path	1 lane	4
Footpath	Only people and animals	5

3.2.4.2. Off-road response

Once it is not possible to keep going by car, the approximation should be made by walking. The mean walking velocity is 5 km/h. However, considering the resistance or friction, given by the slope, altitude and land cover the velocity could be modified.

- Slope. As the slope is increased, there is an increased effort to go up (Figure 3-9). Considering this fact, slope was classified according the friction force to the fire response. Slope friction index is showed in the Table 3-9.

Table 3-9. Slope friction index

Slope percent	Slope friction Index
0-10	1.0
10-25	2.0
25-40	3.0
40-55	4.0
55-65	5.0
65-75	6.0
75-85	7.0
85-95	8.0
95-105	9.0
105-110	10.0
110-115	11.0
>115	16.0

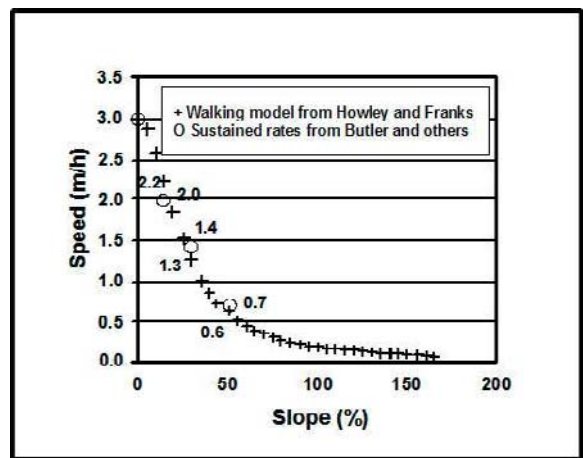


Figure 3-8. A comparison of walking model estimates of a fire fighter's sustainable walking speed with sustainable walking speeds (After [2] and [3])

- Elevation. The elevation can be considered as other factor that delays the response. It can cause negative physiological effects, as reduce supply of oxygen. Therefore, the elevations were reclassified into friction classes and converted to friction values (Table 3-10).

Table 3-10. Elevation friction index

Elevation	Index
1050-1250	1
1250-1450	2
1450-1850	3
1850-2050	4
2050-2250	5
2250-2450	6
2450-2850	7
2850-3050	8
3050-3250	9
3250-3500	10

- Land cover- Arriving to the fire site in absence of roads implies crossing through natural vegetation. Keeping this in mind, land cover was reclassified according the vegetation characteristics described in the previous section into land cover friction values. The land cover friction index is shown in the Table 3-11.

**Table 3-11 Land cover friction index**

<b>Land cover</b>	<b>Index</b>
Bare soil	1
Settlement	2
Grassland	5
Agriculture	6
Pine forest	7
Pine Oak-forest	7
Plantation	7
Oak forest	8
Scrubland	9
Tropical deciduous forest	10
River	12
Lake	15

Once the friction is calculated, a response map was generated. For this, first it was calculated a distance map from the headquarters, using the values of friction as a weight map. Finally, this map was reclassified in homogeneous ranges of 3 km. And reclassified, the more is the distance between headquarter and the fire, the less capacity of response.

### **3.2.5. Static fire risk model**

The static fire risk model is composed by sum of the fuel, ignition, detection and response risk sub-models. In order to determine which is the best combination of sub-models three Equations were compared. Equation 1 is defined by the sum of the models with out weighting. Equation 2 gives more weight to fuel, since this is the element factor for fire ignition and spreading. And finally, Equation 3 gives importance to fuel, but also to ignition since human is the first cause of fires in the study area.

**Equation 1. Static fire risk model**

$$\text{Static fire risk model} = \text{Fuel} + \text{Ignition} + \text{Response} + \text{Detection}$$

**Equation 2. Static fire risk model**

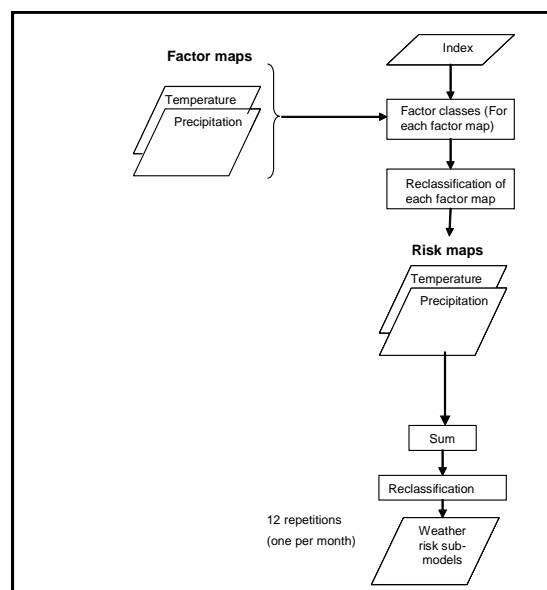
$$\text{Static fire risk model} = (3 \times \text{Fuel}) + (\text{Ignition}) + \text{Response} + \text{Detection}$$

**Equation 3. Static fire risk model**

$$\text{Static fire risk model} = (3 \times \text{Fuel}) + (2 \times \text{Ignition}) + \text{Response} + \text{Detection}$$

### 3.2.6. Weather risk sub-model.

Since the ideal atmospheric conditions for a fire are low humidity and high temperatures [10], the variables considered for the construction of this model were temperature and precipitation. Initially it was planned to develop a model including also the variables of relative humidity and wind (Figure 3-9). However, given the quality of the available data, this model was built using only temperature and precipitation data. It should be mentioned that the probability of a fire's ignition is greatly influenced by the fuel's moisture [83]. The latter is divided into two types: Living fuel and dead (non living) fuel. Dead fuel consist mainly on the organic material (this is non living organisms) deposited on the ground. Its moisture level depends on the surrounding weather and it is considered that as drier as it is found, the higher the probability of a fire's ignition [24,98]. Alternatively, living fuel (living organism, mostly plants, in the surroundings) favour fire spreading more than ignition [98]. Its moisture level could be calculated from the NDVI [99,100]. Given that, one of the main goals of the present study is to solve the question of which are the zones with higher, lower and medium risk of forest fires in the study area. The Weather sub-model can give us indirect information about the moisture level (i. e. how moisture of the dead fuel components could be). Yet, it is highly recommended for further studies the inclusion of fuel's moisture data and wind direction, in order to obtain a more accurate weather sub-model.



**Figure 3-9. Weather risk sub-model**

This model tries to consider temperature and precipitation changes on time. (e. g. dry season and rainy season). The model was considered for each month of the year. For this, data obtained from 32 meteorological stations was used; of which 13 stations are located within the study area and the remaining 19 are located in the surroundings areas. Both data series were obtained from the National Meteorological Service (in Spanish: Servicio Meteorológico Nacional) website ([www.smn.cna.gob.mx](http://www.smn.cna.gob.mx)). Moreover, the precipitation and temperature data are the monthly normal mean average of the data recorded between the years 1977 to 2000. The years with available data varies according to the records of each meteorological station.

Given that, as the altitude increases the temperature reduces, to obtain the general maps of temperature, all the information of every meteorological station was interpolated using a linear regression between the temperature and the altitude for every month of the year (Figure 3-10 and Figure 3-11). Similarly, in the case of precipitation an attempt to find a linear regression between this and the altitude was made. Yet for this study area there it was not possible to develop such relation between these two variables. Precipitation is much more complicated to interpolate than temperature because of its high variability [101]. This could be explained because in Mexico there is a strong influence of other phenomena like tropical storms and hurricanes in the summer or cold fronts in winter [102]. Therefore, an interpolation of the type Moving Average of Inverse distance was carried out to obtain the maps of precipitation. There are other different types of point's interpolation, like the following: Nearest point, Moving average, Moving surface, and Trend surface. Concerning this matter, ILWIS 2.1 Reference Guide defines the method of Moving Average as "The moving average operation is a point interpolation which performs a weighted averaging on point values and returns a raster map as output. In short, the output value for a pixel is calculated as the sum of the products of weights and point values divided by sum weights" [78]. The interpolation method of Moving Average was considered the best for this study, given that there are a considerable number of meteorological stations in the study area. Therefore, the fitting of this method represents the precipitation in a suitable way. This method was compared with the trend surface method with a function of second order and the results are comparable. Yet the trend surface method only shows more general tendencies. Also this method is the most similar to the statistical method of Kriging [103], which is other statistic method used in climatology to interpolate weather variables [103]. Finally, it is important to recognize that the interpolation type applied in this study may be subjected to a certain (but acceptable) error degree, since one of the disadvantages of this method is the lack of knowledge of the fitting accuracy, especially in such variable factors as the precipitation.

To generate the temperature and precipitation fire risk indices the monthly maps were classified homogeneously according to the following simple logic: the hotter and drier areas have the higher fire risk. Table 3-12 shows the temperature indexes and Table 3-13 shows the precipitation indexes. The lower limit for precipitation coincides with the beginning of the dry season. To obtain a map that represents the weather risk, the temperature index and the precipitation index were summed. Finally these maps were summed with the static fire risk model and reclassified homogeneously to obtain the weather sub-models per each month.



**Table 3-12 Temperature index**

<b>Temperature (°C)</b>	<b>Index</b>
0-13.7	1
13.7-17.1	2
17.1-20.5	3
20.5-23.9	4
23.9-28	5

**Table 3-13 Precipitation index**

<b>Precipitation (mm)</b>	<b>Index</b>
0-24.44	10
24.44-71.56	9
71.56-118.68	8
118.68-165.79	7
165.79-212.91	6
212.91-260.03	5
260.03-307.15	4
307.15-354.26	3
354.26-401.38	2
401.38-450	1

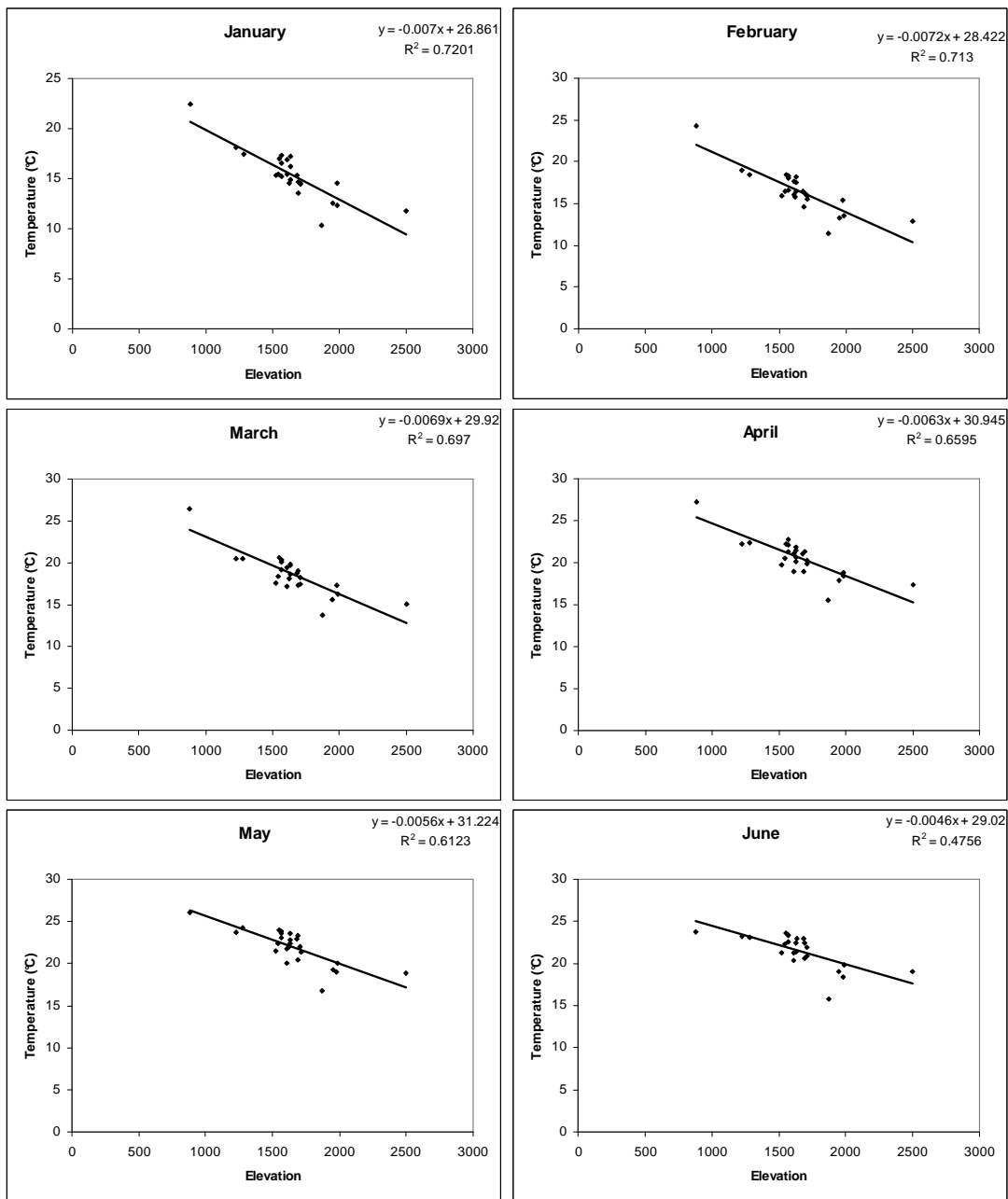


Figure 3-10. Linear regression between elevation and temperature for the months January to June

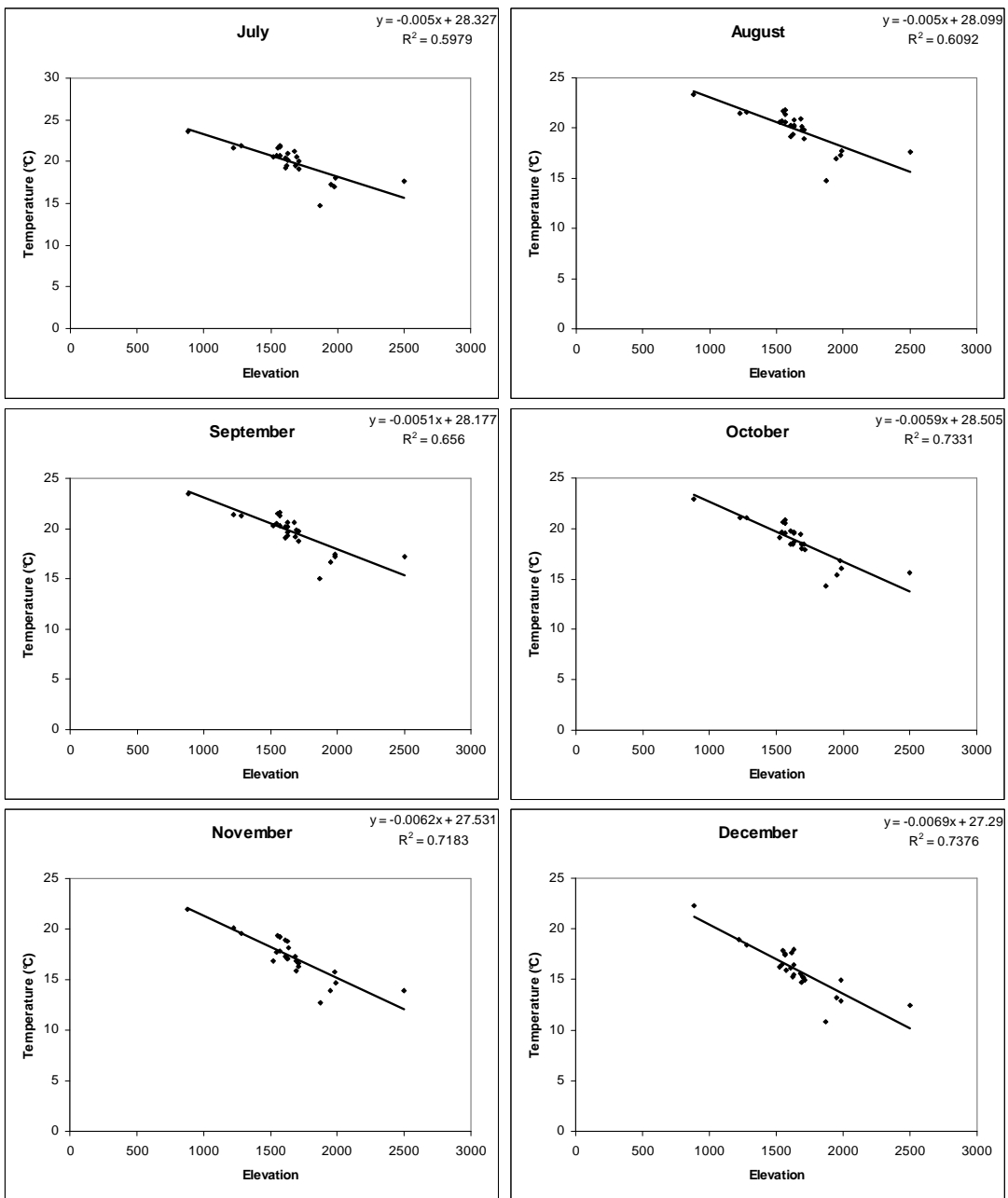


Figure 3-11. Linear regression between elevation and temperature for the months July to December

### 3.3. Validation phase

The accuracy of this model was validated using the burnt area map. This was done for all the sub-models and the final fire risk model, crossing them with the burnt area map. This allowed comparing the real fires with the high, medium and low fire risk areas of the model. The coincidence of burnt scars with the categories will show the level of accuracy of the sub-models. If a high percentage of the burnt scars area coincides with the high risk categories the model will be considered functional. This procedure allows assessing the agreement of burnt area with the forest fire risk model. The obtained results were summarized in tables. In addition, it was applied the Receiving Operating Characteristic analysis (ROC) in the Idrisi Andes v. 15 [104]. The ROC analysis is used to measure the performance of the model and to evaluate classification accuracy. This analysis predicts the location of the fire's occurrence by comparing the probability of fire's occurrence map and a Boolean image that shows where the fire really existed [38]. The ROC analysis shows how the fires are concentrated in a high probability category, and the ROC curve is a plot of the probability of having a true or false forest-fire event [38, 39]. This analysis has been performed with success to assess classifications with ground binary data. ROC analysis has been used in other studies to validate deforestation models [105], land cover change models [106], habitat suitability models [107] among others. Moreover, the Idrisi help [104] states that:

“The Relative Operating Characteristic is an excellent method to assess the validity of a model that predicts the location of the occurrence of a class by comparing a suitability image depicting the likelihood of that class occurring (i.e., the input image) and a Boolean image showing where that class actually exists (i.e., the reference image)...ROC offers a statistical analysis that answers an important question: ‘How well is the category of interest concentrated at the locations of relatively high suitability for that category’ The answer to this question allows the scientist to answer the general question ‘How well do pair of maps agree in terms of the location of cells in a category’ while not being forced to answer the question ‘How well do the pair of maps agree in terms of the quantity of cells in each category’ Thus the ROC analysis is useful for cases in which the scientist wants to see how well the suitability map portrays the location of a particular category but does not have an estimate of the quantity of the category”.

### 3.4. Materials

#### 3.4.1. Cartographic Data and Imagery

In order to develop the fire risk model the following maps and images were employed Table 3-14:

**Table 3-14. Cartography and Imagery used in the study**

ITEM	DATE	CHARACTERISTICS
<b>Imagery</b>		
CONABIO MODIS MOD_14	January to July, 2003, 2004, 2005, 2006	Pixel size: 1 km
ASTER	May, 2006	Pixel size 15 m
<b>Thematic Maps</b>		
Topography		Vector map, esc. 1:250000
Land cover		Vector map, esc. 1:250000
Highways and roads		Vector map, esc. 1:250000
Human settlements		Vector map, esc. 1:250000
Headquarters		Point map
Fire ground record		Point map

In this study three sources of information were used: NASA MODIS images processed by CONABIO, an ASTER image and COFOM's ground records. MODIS hot spots and ground records were required to define the study area. Whereas the ASTER image was used to improve the vegetation map and create a burnt area map. In the following sections are describe the characteristics of each one.

#### 3.4.1.1. IMAGES

##### a) MODIS images

Moderate Resolution Imaging Spectroradiometer (MODIS Spectroradiometers) Terra and Aqua, were launched to space as part of NASA's Earth Observing System in 1999 and 2002, with the purpose of generate information about Earth's surface from specialized products [108,109]. Part of this data are the thermal anomalies products, developed to monitor fires MOD\_14 and MOD\_40, which are designed to detect active fires and to calculate the burned areas [108,110]; this characteristics (Table 3-15) made these products useful tools to understand the spatial and temporal distribution of fires [110].

**Table 3-15 EOS MOD\_14, and MOD\_40 satellite image's characteristics [110]**

	MOD_14	MOD_40
Cover	<b>Day and night</b>	
Space-temporal characteristics	1 km and 10 km and 0.5 degrees /day	1 km and 10 km every 8 or 16 days
Level of process	2 and 3	4

Fire detection is carried out using of an algorithm that utilize the temperature from the thermal channels 21 and 22 of 4  $\mu\text{m}$  (T4) and channel 31 of 11  $\mu\text{m}$  (T11); channel 21 saturates at 500°K (230°C) meanwhile channels 22 and 31 saturates at 331°K (58°C) and 400°K (130°C) respectively [108]. Fire's temperature usually varies depending on the intensity, type and quantity of fuel, and the burning frequency of a determined place; for example, on a prairie in the state of Kansas, USA, a fire's temperatures oscillate between 235.5°C, in a Red Oak habitat, to 78.7°C in a microclimate of the forest's ground [111].

Since 1998 the National Commission for the Knowledge and Use of Biodiversity (in Spanish CONABIO), has been monitoring forest fires by the implementation of the "Program for the detection of hot spots by the use of remote perception techniques". According to this program there are four stages for the fire monitoring, these are: reception and processing of images, fire detection, and publication of information.

MODIS images were incorporated from 2002; first the images from the sensor Terra were received and incorporated and soon after, those from sensor Aqua were incorporated too. Both kind of images are calibrated and georeferenced. Once MODIS images are received, they are processed using MOD14 algorithm, developed by the University of Maryland and by NASA, to detect the hot spots. Later in order to remove the possible false hot spot, different layers (masks) are used in the process. Among the masked layers are: clouds, earth-water boundaries, stable lights and some geographic stable points (*e. g.* Mines, Nitrogen plants, oil wells, etc.). In addition, CONABIO offers thematic cartography to locate the Possible-Fire Points. Finally the fire points are daily uploaded in the CONABIO website, as well as annual, monthly and daily statistics of the occurrence of fires. All the information offered by this institute is contained in a table that shows the exact location of fire events, some of the locality features, visualization of every fire event on a terrain digital model and also over a vegetation model; also they present a map of the fire events' distribution in the country and all this maps are available in format for download to commercial GIS [56].

## **B) ASTER images**

The ASTER sensor (Advanced Spaceborne Thermal Emission and Reflection Radiometer) is also aboard the satellite Terra in December 1999 as a part of NASA's Earth Observing System (EOS) designed and manufactured by the Japan's Ministry of Economy, Trade and Industry (METI) and the Japan's Earth Remote Sensing Data Analysis Center (ERSDAC) [112]. The purpose of this sensor is to obtain information about land surface temperature, emissivity reflectance and elevation [112]. An ASTER scene is a 60 km swath composed by 15 bands divided on three different resolutions: three in the visible and near infrared (0.52-0.86  $\mu\text{m}$ ) (VNIR), six in the short wave (0.6-2.43  $\mu\text{m}$ ) (SWIR) and five thermal bands (8.125 and 11.65  $\mu\text{m}$ ) (TIR) with 15, 30 and 90 m of resolution respectively [113]. These characteristics make ASTER images ideal to study active fires and burnt scales [114]. Composition 6, 3, 1 of bands is also useful to identify the burned areas [37].

### **3.4.2. Ground records**

#### **COFOM records**

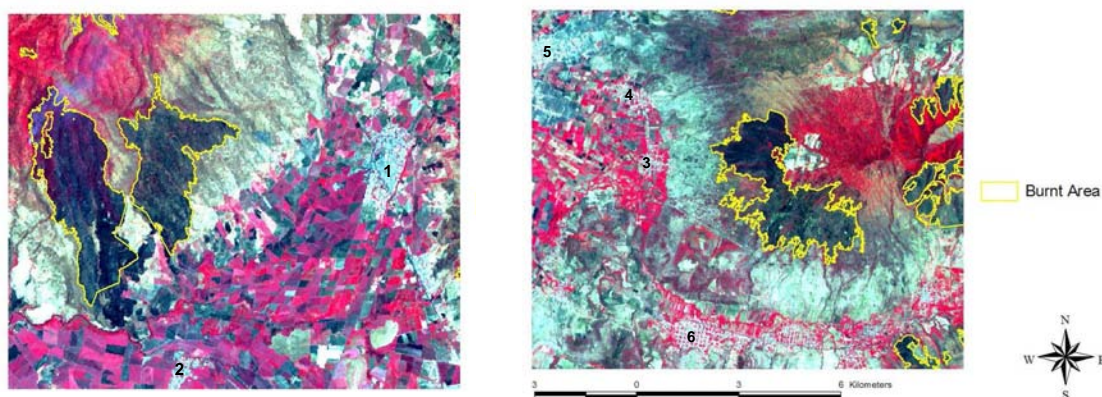
The Michoacán's State Forest Commission (COFOM) is the state's government department in charge of taking action in every aspect related to conservation, encourage, and use of forest resources, according to the law; prevent and fight forest fires through its Department of Forest Fire-fight [14]. Among its functions are the update of the fire's fast detection system, gathering and systematizing of all the fire-related info and elaborate statistical briefs of fire events [115]. Every year this office elaborates and provides a database which contains the records of every fire that they fought within the year. This database provides a lot of information like the location site, municipality, date of the fire's beginning and finishing, fire's length, the vegetation's growing shape (tree, bush, herbaceous), and the name of every person who participated in the fight and control of the fire. Also the COFOM has elaborate maps of the fire critical zones and the location of all the fire fight infrastructure.

## 4. Results and Discussion

### 4.1. Exploratory phase

#### 4.1.1. Burnt Area map

The digital interpretation is a direct method to locate and map areas that have been burnt in past events (burnt scars), using different spectral band combination. Sunar [44] found that the spectral signatures from bands 1, 2, 3 and 4 have a high ability to separate burnt areas from other land cover classes. The selected band combination used in this work (2, 3, 1) has allowed distinguishing the burnt areas easily because of its black tones (Figure 4-1); and finally had lead us to obtain a final burnt map for the study area, shown in Figure 4-2. An advantage of using interpretation and digitalization of burnt areas over supervised classification is that avoids confusion among areas with similar reflectance. This confusion could be present in shadowed areas or in volcanic cone's summit; nevertheless, since mapping burnt areas is not a trivial aspect, it would even better to consider other analyses that could complement the visual interpretation, like NDVI or surface temperature analysis [41], [46]. Burnt area interpretation in scrublands and Oak forests is particularly difficult, due to these areas appeared in greyish to brownish tones. Moreover, due to the frequent burning history of the study area, it is possible to appreciate a considerable number of greyish zones, which they probably not due to recent fires. However, in order to evaluate this, a more detailed database and a more thorough study with extensive field work are needed. However these were not the objectives of the present study. One of the interesting issues that should be mentioned is that most of the burnt areas mapped are beside near to agriculture fields and grasslands.



**Figure 4-1.** Two examples of a digitalized burnt area. Settlements shown in this picture: 1) Santa Clara de Valladares, 2) Los limones, 3) Etucuario, 4) Valle de Guadalupe, 5) Gómez Farias 6) Chilchota



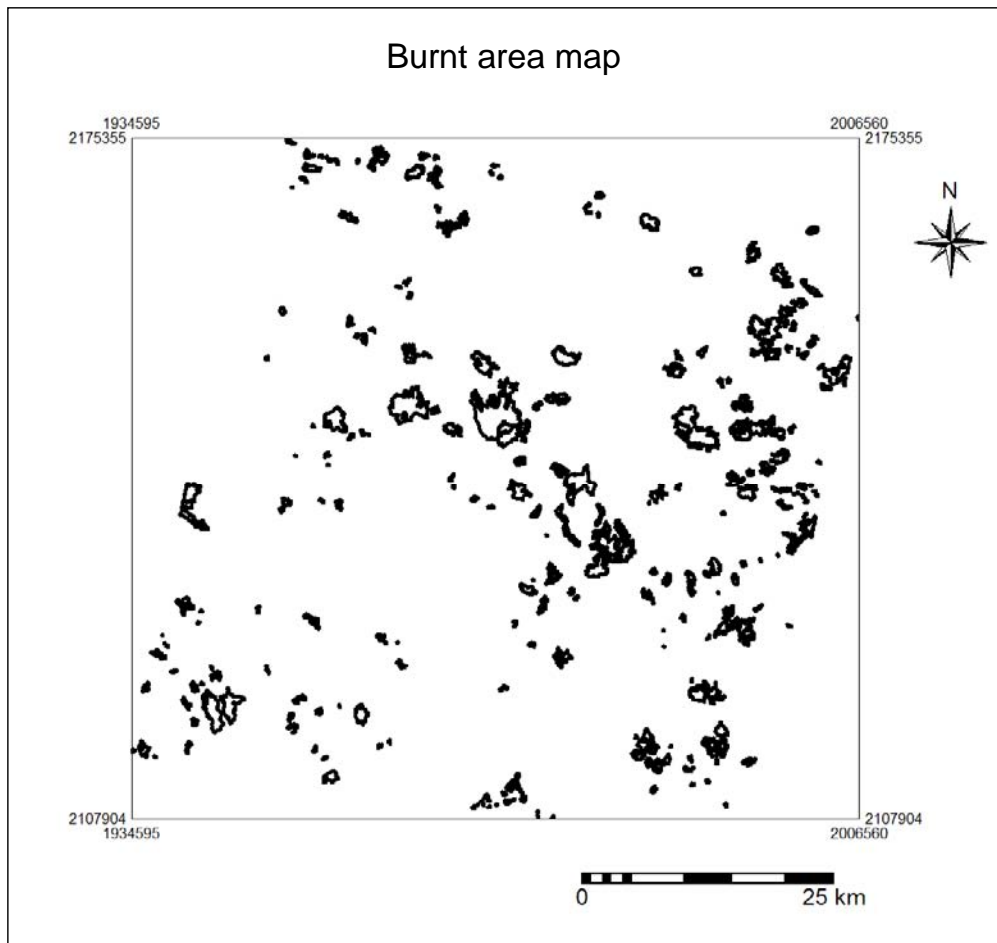


Figure 4-2 Study area Burnt area map

#### 4.1.2. Analysis of biophysical factors influencing forest fire

##### 4.1.2.1. Vegetation type

The presence of fuel is indispensable to generate a fire. Therefore, the characteristics of the vegetation type have big influence on forest fires developing. In the study area the predominant vegetation type is the Pine forest with a total area of 84 250.2 ha. Considering the total burnt area in the different vegetation types, the most affected one are the scrublands, the Oak and the Pine forests (Table 4-1). The burnt surface among them is similar, and it must be considered as an important sign of forest degradation in this area. However, considering the burnt area proportion of Pine forest only a total of 4% was affected by fires, while in the case of Oak and tropical deciduous forests, almost 19% and 17% respectively, of their proportional surface was burnt (Table 4-1). Hence, proportionally to its area Oak forest was significantly more burnt than the other vegetation types ( $H = 21.84$ ,  $P = 0.0002$ ).

During CONABIO's fire susceptible areas workshop [84] it was stated that the habitats with the higher probability of fire occurrence in Mexico, are the Pine and tropical deciduous forests. Moreover, as it was commented in the introduction in Mexico pine forests are commonly affected by

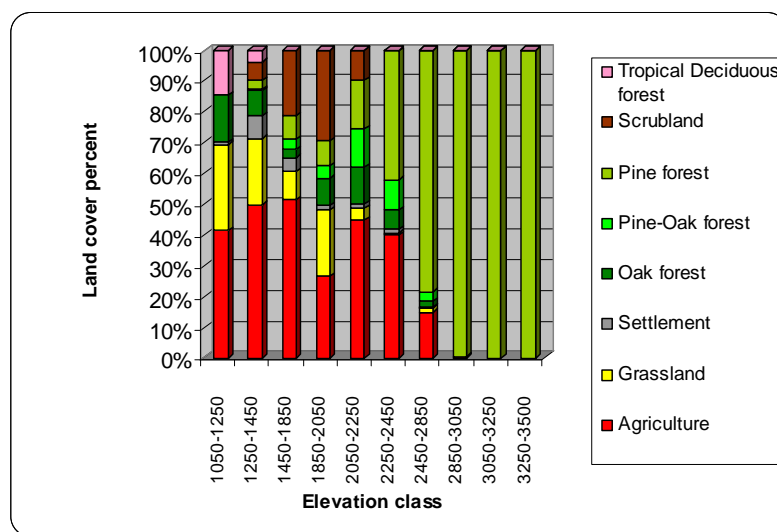
fires [116]. Conversely Oak forests and scrublands are considered to be the type with a lower probability of fire occurrence. The latter differs from the results obtained in this work. This could be explained because Oak forests and tropical deciduous forests are located at low altitudes where they are in contact with agricultural field and grasslands for cattle breeding. On the other hand, Pine forest is located in higher altitudes. If the fires come from agriculture fields they first have to cross Oak forests, which usually are located below Pine forests. In the case of scrublands, although they are located in lower altitudes too, its ability to recover after a fire is high. Moreover, it is known that tropical deciduous forest is one of the most affected vegetations by deforestation and fires [116]. Therefore, the difference between CONABIO workshop and the present results could be explained by the elevation factor.

**Table 4-1. Burnt scars per vegetation types**

Vegetation type	Total surface (ha)	Burnt surface (ha)	% Affection
Oak forest	23665	4388	18.54
Pine forest	84250	4185	4.97
Oak-pine forest	23521	2151	9.14
Scrubland	57902	4316	7.45
Tropical deciduous forest	1009	168	16.67

#### 4.1.2.2. Elevation

Figure 4-3 shows distribution of the land cover classes in relation to its altitude. Pine forest is located in the highlands, while at low and intermediate altitudes is possible to find agriculture fields, grasslands and settlements. The Oak forest is also distributed in this low to medium range. Alternatively, the tropical deciduous forest is located only in areas of less than 1450 m a.s.l altitude.



**Figure 4-3. Altitudinal distribution of land cover classes**

The distribution of burnt areas in relation to altitude are located mainly between the 2000 and the 2800 m a.s.l. (Figure 4-3). As mentioned earlier in methodology, the burnt scar mapping was made

excluding the fires that occurred in non-forested areas (*i. e.* agriculture fields, grasslands and/or settlements). Considering that the original vegetation cover has been modified for human activities at lower elevations, there are less burnt areas at this altitude classes. It also happens that agricultural and grassland fires from the lower areas expand to higher elevations; this occurs because the fire direction; that in absence of wind always goes up-slope [87]. Therefore a great part of the burnt area is located in the elevation classes between 1850 and 2850 m a.s.l. (Figure 4-4). Conversely, at higher altitudes, the fire could extinguish and not arrive to these areas. In addition, the increase of altitude provokes changes in the temperature and humidity that may be influencing this behaviour too.

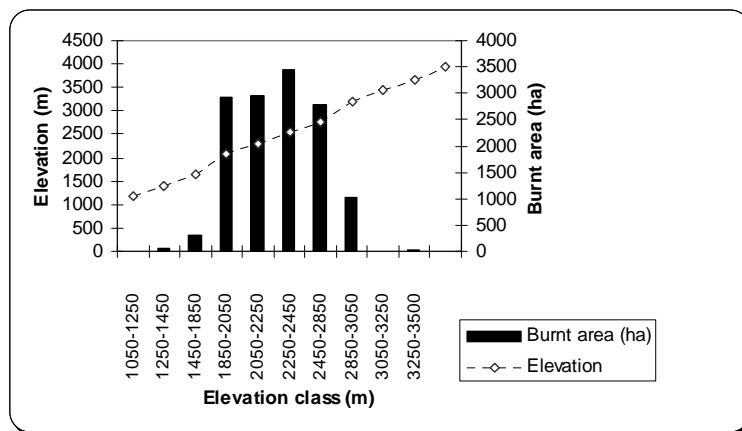


Figure 4-4. Altitudinal distribution of burnt areas

4.1.2.3. Slope

The distribution of burnt scars through different slopes was according to the expected system (See section 3.2.1.2) [87]. The burnt area increases as the slope becomes steeper (Figure 4-5). However, in this case the very steep categories have less burnt area, because this is the category with less total area (Table 4-2) ( $H = 139.2, P = 0.0001$ ). Also it is important to consider that in these areas human accessibility is more difficult.

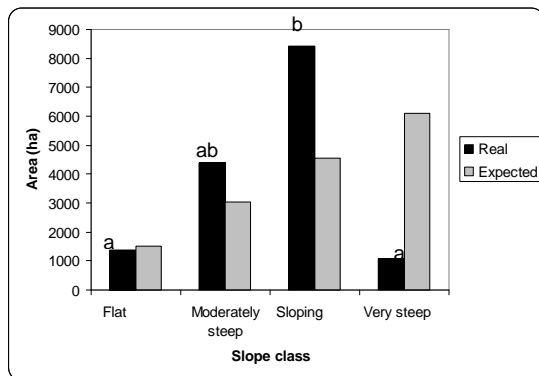


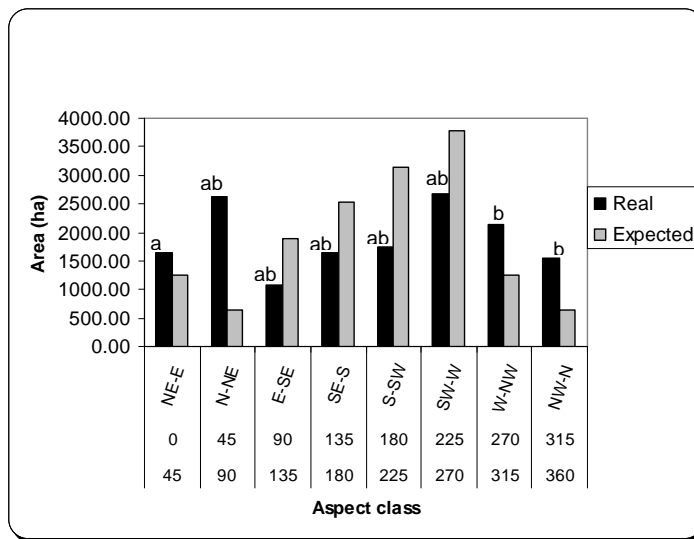
Figure 4-5. Burnt scar distribution per slope class. Letters indicates significance differences among groups

Table 4-2. Burnt scars per slope class

Slope class	Total area (ha)	Burnt area (%)
Flat	336778.27	0.41
Moderately steep	68313.13	6.39
Sloping	219072.65	3.84
Very steep	34899.64	3.07

#### 4.1.2.4. Aspect

The burnt area distribution was significantly different among the different orientation types ( $F_{(7,1671)} = 2.79, P = 0.0069$ ). According to the Tukey test, there are no significant differences among the areas exposed to the south, but among the categories W-NW, NW-N and NE-E. Figure 4-6 shows that the observed burnt area distribution is similar to the expected, except for the N-NE category. As it was expected (See section 0) [92,94], the more burnt areas are those sloping to the SW-W and S-SW (Figure 4-6).



**Figure 4-6 Burnt scar distribution per aspect class.**  
Letters indicates significance differences among groups

#### 4.1.2.5. Ignition factors

Official reports in Mexico consider human activities as the primary cause of fires [11,17,64]. As mentioned earlier, in the State of Michoacán the burning of grasslands is the main activity that provokes forest fires; leaving the crop field burning as the second cause of fires. In the study area both activities take place during the dry season. Figure 4-7 A and B represents the distribution of the burnt scars in relation to the distance to growing fields and grasslands. In both figures is possible to observe that in close proximity of crop fields and grasslands there is a more burnt surface, but as this distance increases the burnt surface decreases. For example in the first 500 m following to crop fields and grasslands a burnt surface of about 2500 to 5000 ha were recorded. As agriculture is the main economic activity in the zone, this appears to influence the distribution of the burnt areas.

In contrast, the border effect that exists in the surroundings of roads and highways produces a reduction in the vegetation cover that causes an increase in the ground temperature [95]. Moreover, these highways give people access to natural or remote areas. In the study area, the closeness to roads and highways increases the areas of forest fires. For instance in the first 500 m close to roads and highways, a total burnt surface of 4000 ha was found (Figure 4-7 D). Nonetheless, it is important to mention that roads and highways usually cross crop fields as well as grasslands. Concerning the

presence of human settlements, the relation is exist but it is showed after a distance since the fields of agriculture and grass are outside the settlement in a distance beyond 2 km; then the relationship is shown (Figure 4-7 C). However, more data is needed to analyze the degree of influence in the distribution of fires due to the presence of human settlements.

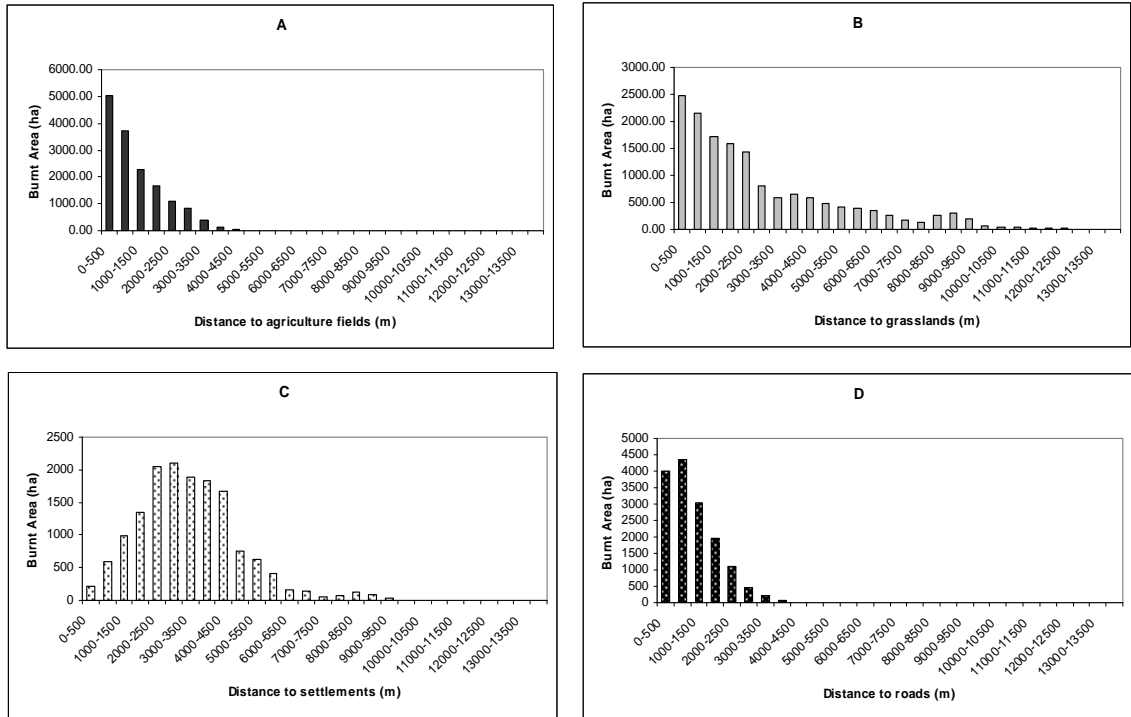


Figure 4-7. Burnt scar distribution according to distance to (A) Agriculture fields, (B) Grasslands, (C) Settlements, (D) Roads

#### 4.1.2.6. Weather

The fire season takes place in the first half of the year (January to June) [61]. Of these, the most incidences of fires occur in April and May (Figure 4-8). Although the incidence of fires does not occur as a direct consequence of the climatic conditions in Mexico, it is clear that the high temperatures and the low precipitation that take place in the mentioned months (Figure 4-10 and Figure 4-9) make the fuel gets dry. Such condition favours that fires may spread to natural areas during the burning of crop fields and grasslands [3]. Moreover, it is known that fires originated by people have more influence when the natural conditions are appropriate to fires [117].

## 4.2. Modelling phase

### 4.2.1. Fuel risk sub-model

The fuel risk model is considered as one of the most important models since it includes indispensable variables for the forest fires like vegetation type, slope, aspect and elevation [82]. As stated in the previous section all these factors have a great effect on forest fires in the study area. The vegetation types define the risk areas, whereas the topography, in particular the southern aspect, intensifies the risk. After integrating all the factors, it was identified the maximum, high, medium and low risk areas were identified. Medium risk is the predominant class; whereas maximum risk and low risks were identified in similar proportions (

Table 4-3). The low risk area corresponds mainly to non forested areas such as agricultural fields, grasslands or cities. The medium risk is also composed of agriculture fields and grasslands; however it is located surrounding natural vegetation, since fires started in these places usually spread to forested areas. This class also includes areas with natural vegetation located in low areas such as scrubland or in very high altitudes. The areas classified as high risk have steep slopes and belong to natural vegetation, mostly Pine or Oak forest. Likewise, the maximum risk areas are those that fulfil all the favour conditions for a forest fire. This is southern steep slopes and natural vegetation as Pine, Oak or tropical deciduous forest. Finally, the no risk area belongs to water bodies, or bares soil. The fuel risk sub-model is showed in Figure 4-12.

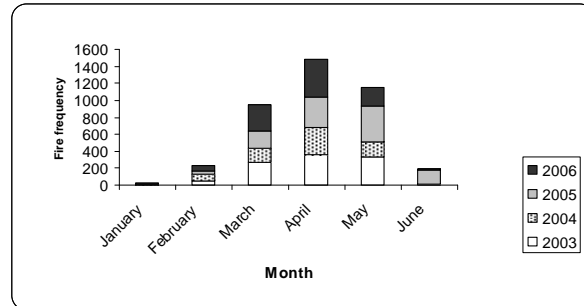


Figure 4-8. Fire frequency in the dry season from 2003 to 2006

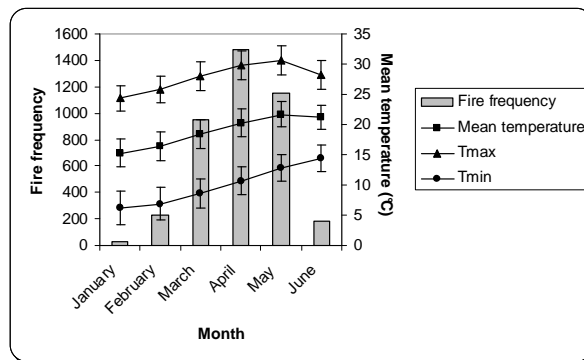


Figure 4-9. Fire frequency and temperature (°C), temperature of the first six months of the year.

Tmax = Maximum temperature and Tmin= Minimum

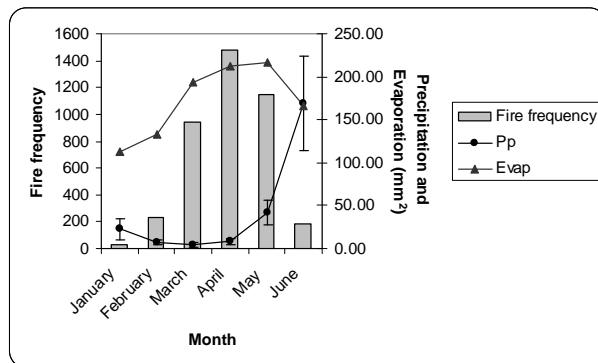


Figure 4-10 Fire frequency of the first six months of the year. Pp = mean precipitation (mm) and E= evaporation

Table 4-3. Area (%) per risk category of Fuel risk sub-model

Fuel fire risk	Area (%)
Maximum	9.28
High	24.59
Medium	42.8

#### 4.2.2. Ignition risk sub-model

The ignition model is related with human activities like agriculture or stock farming or with human settlements or roads. In the exploratory phase it was observed a direct relation among these variables and forest fires. Due to this in this sub-model it was included a category source of risk based on these human areas. The percentage area occupied by the ignition risk categories is shown in Table 4-4. The maximum and high risks are located in areas limiting with agriculture fields, grasslands and highways. In the other hand the minimum risk is located in the highest areas where no settlements or human activities are present. The ignition risk sub-model is shown in Figure 4-13.

**Table 4-4. Area (%) per risk category of the Ignition risk sub-model**

Ignition fire risk	Area (%)	Ignition fire risk	Area (%)
Maximum	6.15	Moderate	5.38
High	21.13	Low	2.12
Medium	12.17	Minimum	1.20
		Source of risk	51.54

#### 4.2.3. Weather risk sub-models

As mentioned earlier, in Mexico the fire season occurs mainly from January to June, although sporadic fires may take place during the second half of the year. The weather risk model was made for the 12 months of the year as a comparative exercise. During the dry season, it is observed that the areas classified as maximum, very high and high risk increases with respect to the rainy months. An example of this is April as this month is the driest and hottest month; it is the month with the highest number of fires of the year. The map corresponding to this month shows more areas classified as high risk than the rest of the year (Figure 4-18). Conversely, in the rainy season the risk decreases as Figure 4-17 shows, which represents the risk of fire during August. A more detailed distribution of the risk zones through the whole year is presented in Appendix 5.5.

The weather sub model developed in this study is a temporal model that provides twelve-month scenarios. It uses the average data for both temperature and precipitation, without considering the annual or daily variability in both features. Consequently, the model does not include the changes in temperature and precipitation caused by “El Niño” phenomenon, which has a high influence in the fire frequency in Mexico. It has been reported that, during the “El Niño” years the fire’s incidence increases significantly in contrast with other years. A clear example of this is 1998 when the national record of fires was of 14,445, causing severe ecological and economical damage to the country [11,57,60]. However, this model will not predict the change of forest fire-risk according to the daily or annual fluctuations in temperature and/or precipitation. It is worth to mention that including dynamic meteorological data represent a challenge in Mexico. The scarce of meteorological stations as well as the insufficiency and the poor-quality of forest fire records, makes difficult the application of predictive modeling that associate the fire’s incidence with the temperature and precipitation changes. Thus, factor’s correlation analyses from the data obtained from meteorological stations are ruled out

in the modeling of forest fire risk. In addition, the location of these stations is biased to settlements instead of the forested areas. GIS allows to acquire meteorological data easily and of better quality. An example of this is the work of Manzo [60], who uses a Logit model in order to predict the fire's incidence from NDVI values and surface temperature for the years 1997 to 2000. Nonetheless, there is no climatic model so precise that could be continuously updated with information obtained from satellite and that can be incorporated to a fire occurrence predicting model. One of the virtues of the proposed sub-models of this study is that they show possible forest-fire risk scenarios throughout the whole year, pointing out the areas with the higher risk per month. However, their function is not predictive.

As mentioned before, the sub-models elaborated in this study show the distribution of the highest risk zones through the year. These sub-models highlight the high risk areas. For example, despite the fact that during the rainy season the occurrence of fires is low, it is worth to consider the zones classified as high risk during the whole year. The spatial location of the risk zones through the different seasons of the year, essentially on the dry season, may help to elaborate strategies to prevent fires or to minimize the damages caused by them. Nevertheless, it is important to consider that the present model only considers two variables: the precipitation and temperature. Therefore, in order to improve this model in the future it is highly recommended to include data for the fuel's humidity, air humidity, wind speed and direction.

**Table 4-5. Area (%) per risk category of April sub-model**

April fire risk	Burnt Area (%)
Maximum	6.6
Very High	12.9
High	51.0
Medium high	26.4
Medium	2.8
Moderate	0.2
Low	0.0

**Table 4-6. Area (%) per risk category of August sub-model**

August fire risk	Burnt Area (%)
Maximum	0.0
Very High	0.2
High	13.5
Medium high	46.4
Medium	34.8
Moderate	4.7
Low	0.3

#### 4.2.4. Detection risk sub-model

The detection risk sub-model shows hidden areas for the human eye, where a fire cannot be detected for a certain period of time. Since the study area is a high populated area a high percentage of surface is visible from cities, roads and forest towers. However, there are still some areas that remain as non visible (Table 4-7). The invisible areas belong mainly to highest altitudes or ravines. But, some areas among mountains or far from roads are invisible too. This sub-model allows identifying these areas and it can help in the decision making to locate new forest towers or forest camps.

**Table 4-7. Area (%) per risk category of the Detection sub-model**

Detection	Area (%)
invisible	24.16
visible	75.84



#### 4.2.5. Response risk sub-model

The response risk sub-model shows that 36% of the study area is in an area of maximum to high response, the 42% shows a medium to moderate response and 6% appear to be in a low to minimum response (Table 4-8). The distribution of these areas is shown in Figure 4-15. However, it should be mentioned that the results within the limits of the study area have a border effect. The bigger area was considered and of the original size was done. The distributions of the response areas are not at random. Because of that there are 15 headquarters available in the area, from which the fire fighters brigades depart. Almost all the headquarters are located to in the southwestern part of the area. The zones where there is a longer time of response are in general those where the altitude is high. This means that there is more distance between the headquarters located at lower altitudes and flat terrains and the potential fires in high altitudes. An important issue of this model is that, it also considers the friction. The variety of responses depends on slope, type of vegetation cover and type of roads. Steep slopes or very dense vegetation types could be difficult to pass through the brigades. Considering this friction values, the longest distance that should be crossed to arrive at the location of a fire would be 178 km, and considering that the average vehicle used reaches a constant speed of 60 km/hr the estimated time of arrival would be of approximately 3 hours. According to the data obtained from CONAFOR, the national average time of fire's detection in 2005 was 37 minutes, with a time of arrival at the site of one hour and 12 minutes, and the average time of fire fight's duration of 13 hours and 40 minutes [11]. For the 2006 the same office reported that the average detection time was of 37 minutes, the average response time of one hour and duration time of 13 hours and 19 minutes [11]. Currently, Mexican government is making efforts to improve these average times with the purchase of more vehicles (mainly terrain trucks) and giving a much better capacity for the staff.

**Table 4-8. Area (%) per risk category of the Response sub-model**

<b>Response risk</b>	<b>Area (%)</b>
Low	1.17
Minimum	4.40
Moderate	14.18
Medium	28.07
High	34.27
Maximum	17.92

#### 4.2.6. Static Fire Risk Model

In order to construct the static fire risk model three Equations were compared (Figure 4-11). Equation 1 is the sum of the four static models with out weight, Equation 2 gives more weight to fuel and Equation 3 includes ignition as the second factor in importance (See Section 3.25). In spite of the fact that the three Equations give different weights to fuel and ignition sub-models the distribution of burnt scars is similar in most categories. The main difference in the distribution of burnt scars among the three tested equations was concentrated in the moderate and low categories. Equation 1 shows more burnt area distributed in moderate risk, whereas Equation 3 had more burnt area in the low risk

category. Equation 3 adds more weight to ignition than the other two equations. Therefore, this difference between the low and moderate risk mentioned above can be explained because the model is having more emphasis in Equation 3 on agriculture fields and grasslands as a high forest fire risk zones. Ignition model consider that these areas are continually burned and fire can spread from them to forest. However, agriculture fields and grasslands are non forested areas, and are not of the interest of this study. Equation 3 was chosen to calculate the static model, since it gives high weight to the two of the main factors to start a fire: fuel and heat (ignition sources). In the following paragraphs the results of the static fire risk model are described.

The static fire risk model takes into account all the factors included in the fuel, ignition, detection and response sub-models (Figure 4-16). The global result of the sum of all sub-models is the final but static Fire Risk Model. According to this model the resulting percentages are: 26% of the forest’s area considered in the maximum and very-high risk values, 29% is categorized as medium-high to moderate risk and 45% is categorized as low to minimum risk (Table 4-9). As it was mentioned in the introduction the basic elements to fire starting are fuel, oxygen and heat [1]. Once a fire starts, spreading occurs as an effect of fuel characteristics (mainly its accumulation), topography and weather conditions [118]. For both, starting and spreading, fuel characteristics are essential. As a result of this, the weight of fuel and ignition sub-models has a great importance in the final static fire risk model. The study area topography and cover types play a key role. In this respect, the areas considered in the very high risk category are those with a vegetation type of Pine, Pine-Oak and Oak forest, which are located in the lower zones of the highlands. Besides, some of the areas classified as maximum and very high risk correspond with the southern orientation of the slope. In contrast the areas with the lower risk values, they correspond with the absence of natural vegetation cover, like the cities, agriculture fields, and grasslands; which are also found in low and flat terrain. The fact that a large proportion of the study site is found among such land uses categories, explains the high percentage value categorized as low risk. On the other hand the effect of the ignition source reflects a clear increase of the risk in the boundary of the natural vegetation cover close to roads, crop fields and grasslands. As for the areas of medium risk, their distribution is more heterogeneous in the different vegetation types at medium altitudes. The effect of the detection and response sub-models is not so evident in the final map of the fire risk static model, since both occur once the fire is started.

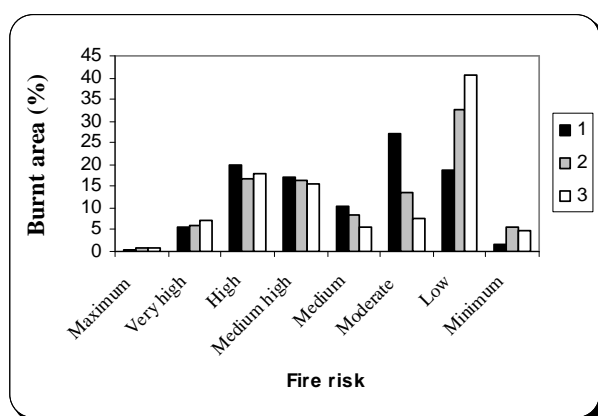


Figure 4-11. Percentage of burnt area by fire risk class using Equations 1, 2 and 3

Table 4-9. Area (%) per risk category of Static fire risk sub-model

Fire risk	Area (%)
Maximum	0.94
Very high	6.98
High	17.78
Medium high	15.42
Medium	5.53
Moderate	7.76
Low	40.55
Minimum	4.69
No risk	0.34

Fuel risk Map

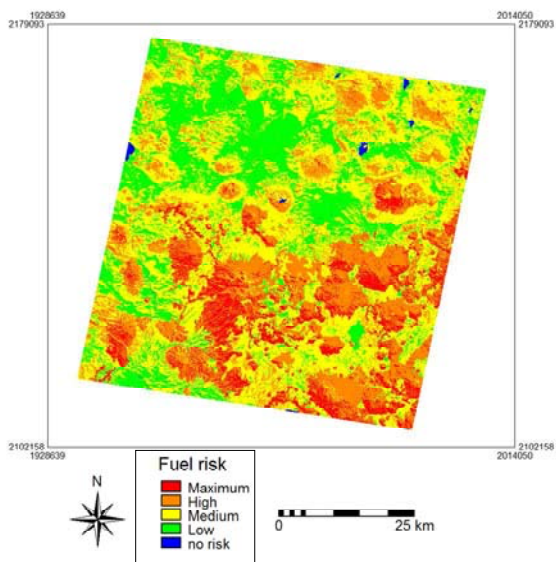


Figure 4-12. Fuel risk map

Ignition risk Map

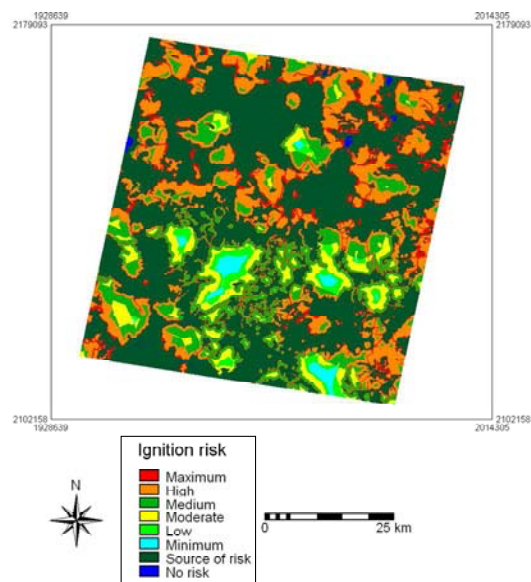


Figure 4-13. Ignition risk map

Detection Map

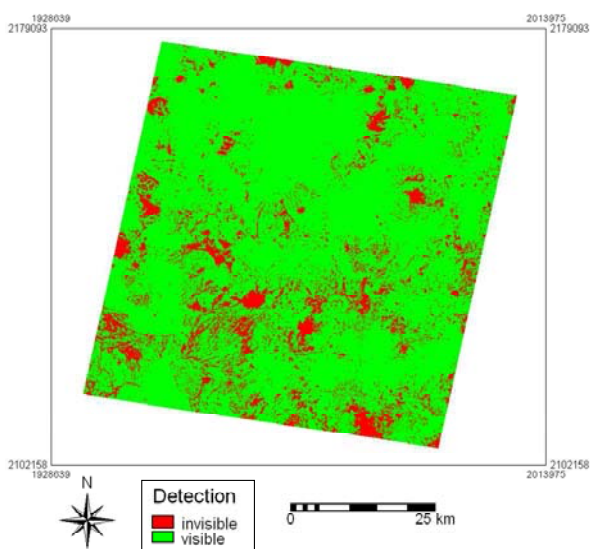


Figure 4-14. Detection map

Response risk

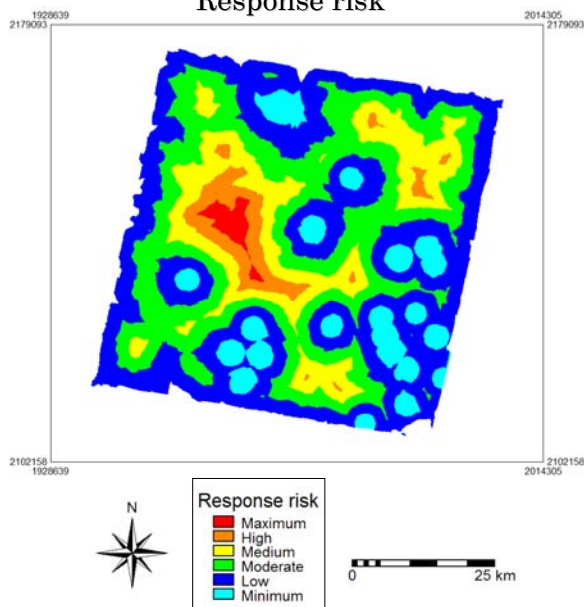
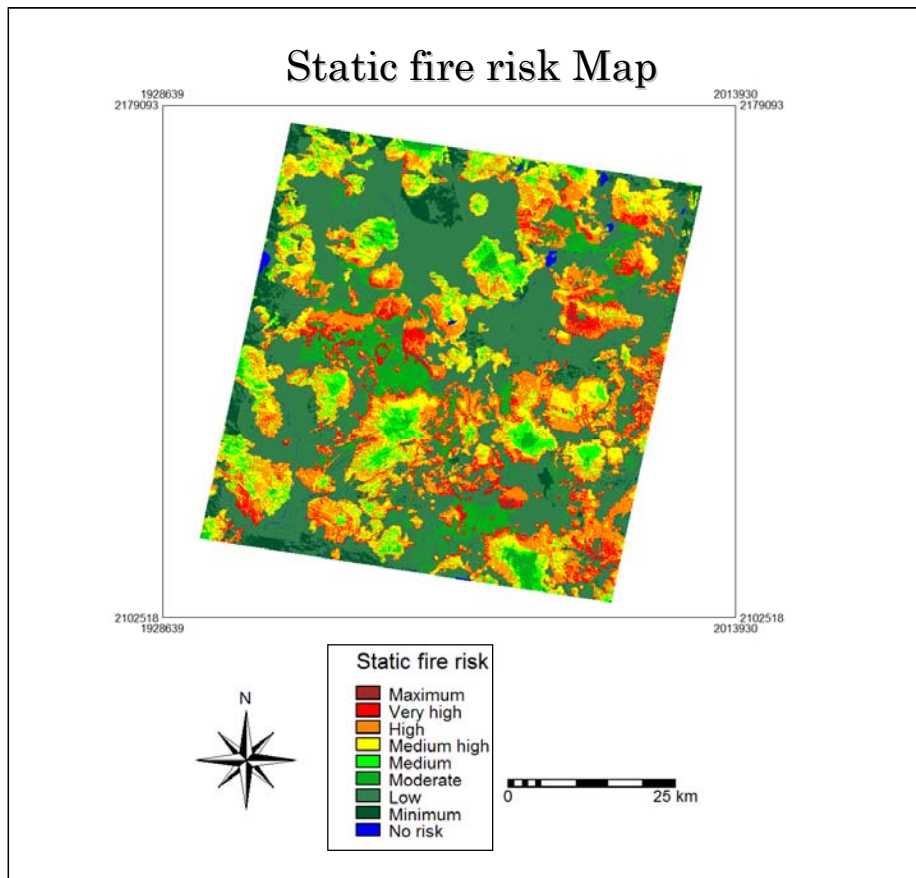
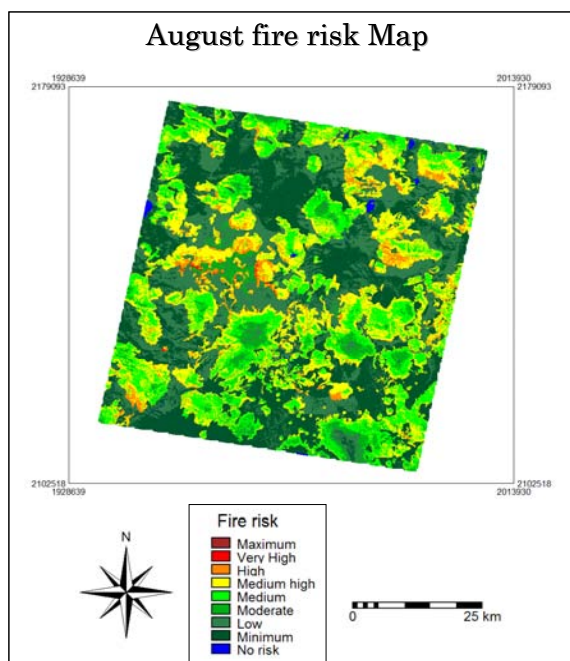


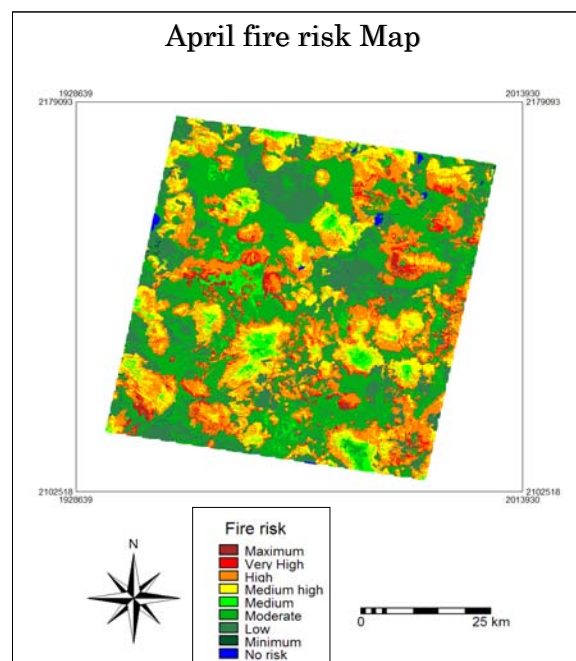
Figure 4-15. Response risk map



**Figure 4-16. Static fire risk**



**Figure 4-17. August fire risk**



**Figure 4-18. April fire risk**

### 4.3. Validation

The validation of the forest fire map of risk sub-models was performed by crossing the burnt areas map with the sub-models maps and the final fire risk model. For the sub-models fuel and ignition the burnt scars were distributed mainly in the maximum to medium high risk categories (Table 4-10 and Table 4-12). On the other hand, the detection model shows that a great part of the burnt area was visible from certain point (Table 4-11). The high number of settlements and the complex road network can explain this fact. However, it is important to consider that the detection of forest fires is also a more complex issue. It can vary depending on the time of the day and also is important to consider that some roads are more passable than others. In the case of the response sub-model, 39% of the burnt scars were located in the areas classified as maximum and high response, 52% in the moderate to medium response and 9% in the low to minimum response (Table 4-13). The distribution of the burnt areas in the response model shows that just a few burnt areas were located in the most inaccessible areas, whereas the burnt area increases as the areas are more accessible. This coincides with the fact that the nearest places to roads are the areas with more percentage of burnt scars because fires are mainly associated with human activities.

The static model had a high agreement with the burnt scars and the high risk categories, since 91% of the burnt scars were located mainly in the maximum to high medium risk category (Table 4-14). Based on Figure 4-19, we can say that the efforts of fire risk management should be directed mainly to medium high, high and very high risk areas because in the other categories the burnt area is very small. Since this model includes the information of the fuel, ignition, detection and response sub-models and is the base for the weather sub-models, a ROC analysis (Receiver Operation Characteristic) was applied to test the accuracy of the model. The static model was very accurate to classify the fire risk categories (ROC = 0.8). Figure 4-20 shows the ROC curve developed for this model. A ROC curve is constructed by contrasting the true positive rate against the false positive rate which corresponds to real burnt area and area by category of the static risk, respectively. This figure can be read in the following way: a) assuming that the 10% of the area has been burned, a perfect model would classify the same percentage of area as maximum or high risk, and therefore the ROC coefficient would be 1. This perfect prediction corresponds to the OA line of the graph; b) On the other hand, if the burnt area does not coincide with the high risk categories and its distribution is random, the curve would be under the line OM and the ROC coefficient would be 0 [105]; c) According to this, the ROC curve for the static fire risk model shows that the performance of the model is very good since 80% of the area below the curve OBM is over the diagonal OM. Here it should be mentioned that the role of the fuel and ignition model was fundamental in the elaboration and functionality of the static sub-model. In the cases where the weather sub-models had a high percentage of burnt scars in the high risk categories for the months of dry season, then for the months of rainy season the risk diminishes for the same areas. This result is in agreement with the expectation. For April 97% of the burnt scars were located in the high risk categories, whereas for August it was 60%. Moreover, Table 4-15 and Table 4-16 show the burnt area distribution of the months of April (driest) and August (wettest). To see other months, see the tables in Appendix 5.5. Finally it should be mentioned that in general the accuracy of the model was considerably high since almost all the burnt scars were located in the high risk class.

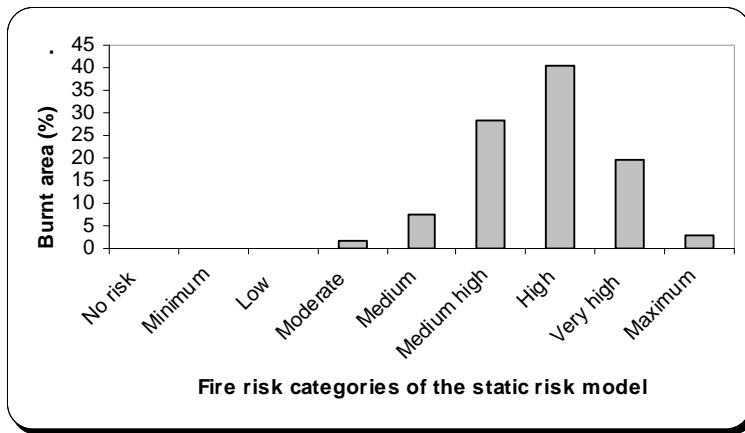


Figure 4-19. Distribution of the burnt scars in the fire risk categories of the static risk model

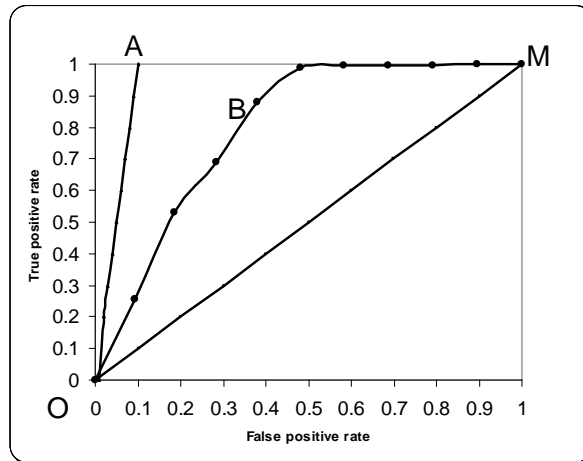


Figure 4-20. ROC curve. Lines OA correspond to a perfect model, OM to a null model and OBM to the static risk model.

**Table 4-10. Burnt area (%) per fire risk category for the Fuel sub-model**

Fuel fire risk class	Burnt Area (%)
Maximum to high	63.0
Medium	34.3
Low	2.7

**Table 4-11. Burnt area (%) per fire risk category for the Detection sub-model**

Visibility	Burnt Area (%)
invisible	17.9
visible	82.1

**Table 4-12. Burnt area (%) per fire risk category for the Ignition sub-model**

Ignition fire risk class	Burnt Area (%)
Maximum to medium	89.0
Moderate to minimum	10.6
Source of risk	0.32

**Table 4-13. Burnt area (%) per fire risk category for the Response sub-model**

Response	Burnt Area (%)
Moderate to minimum	29.6
Maximum to medium	70.4

**Table 4-14. Burnt area (%) per fire risk categories for the Static sub-model**

Static fire risk	Burnt Area (%)
Maximum to medium high	91.0
Medium to minimum	9.1

**Table 4-15. Burnt area (%) per fire risk category for the month of April**

April fire risk	Burnt Area (%)
Maximum to medium high	97.0

**Table 4-16. Burnt area (%) per fire risk category for the month of August**

August fire risk	Burnt Area (%)
Maximum to medium high	60.1

#### 4.4. Relevance of the obtained results

The forest fire risk model proposed in this study is a very helpful tool to prevent forest fires, which can be a very helpful addition to the development of the national forest fire management program. The proposed model of this study was carried out in a similar condition to those found in several inter-tropical regions of Mexico. For instance, the burnt of agriculture fields and grasslands is a common practice in most of the country. Such activity is carried out mainly in the less developed and poorest areas. Therefore, this model would be of help to the people of this region, who requires a better strategy for monitoring, supporting and control of the fires.

It should be mentioned here that the development of this fire risk model will have more significance in a global climate change scenario, where high temperature and aridity conditions provoke an increase in the number of fires. As a consequence, their detection and prevention will be a priority. This model can be used easily to identify, with a relatively low cost, the areas more prone to fire, where the prevention efforts should be made.

The present model includes the more important biophysical and social variables. Comparing with other models developed for the detection of fire risk, this one coincides in using several variables like elevation, slope, aspect, vegetation type and the distance to roads, settlements and agriculture fields [1, 5]. Four approaches forest fire modeling presented by Chuvieco [5] are: 1) Qualitative and quantitative models based on expert knowledge, 2) Quantitative models based on multi-criteria evaluation 3) Models based on statistics, in which neural network models are included and 4) Meteorological or fire dispersion models. These approaches include an ample variety of methods for the development of risk's maps. However, since the actual information on the fire's records in Mexico does not include fire frequency or their precise location in geographic coordinates, it is not possible to built statistical models to correlate the occurrence of fire with other type of variables. For this reason, the significance of this model is that it can be applied to different regions, allowing identifying higher risk areas. Moreover, the validation of this model will allow its implementation in similar regions in Mexico.



## 5. Conclusions and Recommendations

### 5.1. Conclusion

The general objective of this study is to model forest fire risk for a critical zone in Michoacán, Mexico.

This objective was accomplished since the fire risk model, identified appropriately the high, medium and low fire risk areas. The static model showed that: 25.7% of the forest surface is in the maximum and very-high risk; 28.7% is categorized as medium-high to moderate risk and 45.2% is categorized as low to minimum risk. On the other hand, the weather sub-models showed the changes of fire risk through the year and high coincidence with the burnt areas.

In order to develop the fire risk model, four specific objectives were considered. The specific conclusions are summarized in the paragraphs below.

#### **1. To detect and map forest burnt areas using a high resolution ASTER image**

##### **Q1. Can burnt area can be detected and mapped using a high resolution ASTER image?**

The ASTER image successfully allowed detecting and mapping the burnt areas using the band combination 2,3,1. The estimated area affected by forest fires was 15,200 ha of the total area (394,200 ha). Based on this map the factors influencing forest fires were evaluated.

#### **2. To analyze the main factors related to forest fires in the study area**

##### **Q2. Which of these factors are more related to fire through its relationship to burnt areas?**

There was a clear relationship between distance to agriculture fields, distance to grasslands and distance from roads to forest areas, since burnt areas increases as distance decreases. Topography has an important effect too. The burnt areas are distributed mostly in steep slopes with southerly aspect and located in mid-elevations. Finally, Pine and Oak forests seem to be the most affected vegetation types. Areas that show all these characteristics were classified as high to maximum risk in the final fire risk model (See the following conclusion).

#### **3. To develop a forest fire risk model for the study area in order to identify the fire prone areas.**

##### **Q3. Which are the prone fire areas (high, medium and low fire risk) in the study area?**

The fire risk model was developed by integrating the fuel, ignition, detection and response sub-models. This model is considered as static fire risk model since it does not include weather variable. Ignition and Fuel sub-models are the most effective components of the final model, since their

components are essential contributing to fire start and spread. On the other hand, the detection sub-model shows that most of the study area is visible from cities, roads or forest towers. But it also highlights the areas where fires are not visible in the fire start stage. According to the response sub-model 36% of the study area has a maximum to high response, 42% a medium to moderate response and 6% is in a low to minimum response. The variety of responses depends mainly on slope, altitude, type of vegetation and type of roads. Steep slopes or very dense vegetation add more resistance to the fire brigade to pass through to the forest cover. In this case, the areas with less efficiency of response are those located at high altitudes. On the other hand, weather sub-models showed differences among the hottest and driest months and rainy season months. April is the month with more high risk of the year, whereas August is the month with least risk. These facts coincide with official fire statistics that show that temporal tendency of fires over the year.

#### **4. To validate the forest fire risk model**

##### **Q4. How accurate is the forest fire risk model developed in this study?**

The validation of the static and weather fire risk models was successful for the study area, since more than 91%, 97% and 60% of the burnt areas were located in the very high to high risk categories in the static, April and August models, respectively. Moreover, a ROC value of 0.8 supports the accuracy of the prediction. In summary the GIS modelling applied in this study allowed the elaboration of an accurate forest fire risk model. Consequently, the obtained results are appropriate to elaborate future prevention strategies in the study area. Moreover, the simplicity of this model allows the incorporation of new variables or the realization of adjustments in order to improve the obtained results.

## **5.2. Recommendations**

Finally, the recommendations for further studies are:

- It is recommended that the visual interpretation is complemented with other techniques such as the analysis of NDVI values or surface temperature analysis.
- It is highly recommended to incorporate fuel's humidity, air humidity, wind speed and direction data in the weather sub-model.
- Fires frequency increases with meteorological phenomena such as "El niño". Therefore, for fire prediction it is recommended to incorporate updated weather data.
- The inclusion of additional data such as vegetation density or biomass maps could improve the results of this study.

Other recommendations:

- This model could be reproduced in other study area since it's operationally simple.
- Since almost all the processes are carried out in the freeware software e.g., Ilwis, the applied method is cost effective and it could be easily implemented in other areas in the country.

- Since human activity is the main cause of forest fires in Michoacán state it is recommended develop more prevention strategies with local people.
- The weather sub-models showed that there are areas located in constant risk the whole year. It is recommended to give higher consideration to these areas in a fire management plan.
- The implementation of fire-break lines is recommended for the high risk areas where brigade response is low.

Finally, the outputs of this study contribute to:

- Detect burnt forests using high spatial resolution of ASTER images.
- Analyze biophysical and social factors affecting forest fire in the test area of Michoacán, Mexico.
- Develop a forest fire risk model for the test area of Michoacán, Mexico.
- Develop a multi-temporal dynamic sub-model for the above mentioned Forest Fire Risk Model.
- Develop forest fire management recommendations for the test area of Michoacán, Mexico.

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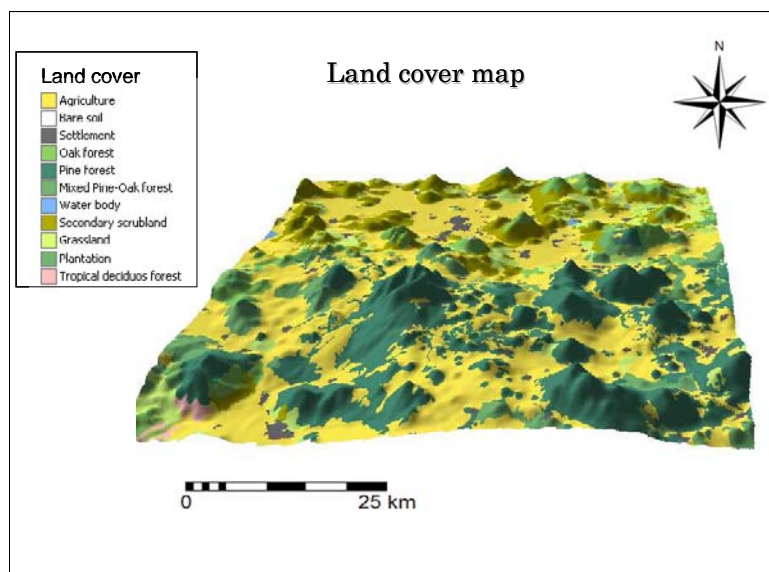


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## Appendices

### 5.3. Land cover map



### 5.4. Vegetation types



Pine forest



Oak forest



Tropical deciduous forest



Secondary scrubland



Grassland



Agriculture fields

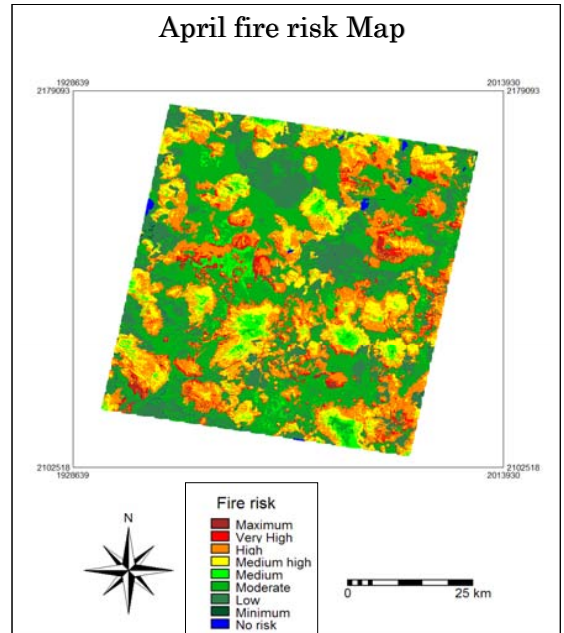
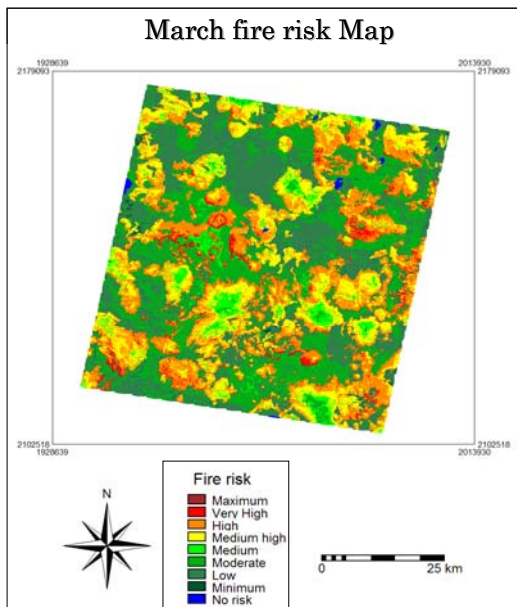
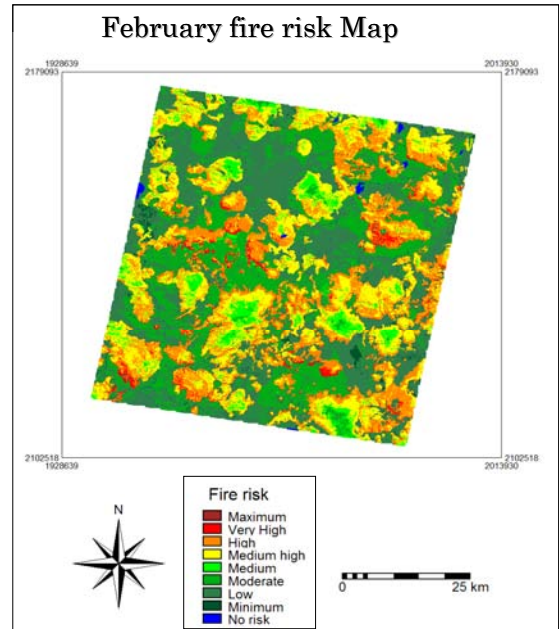
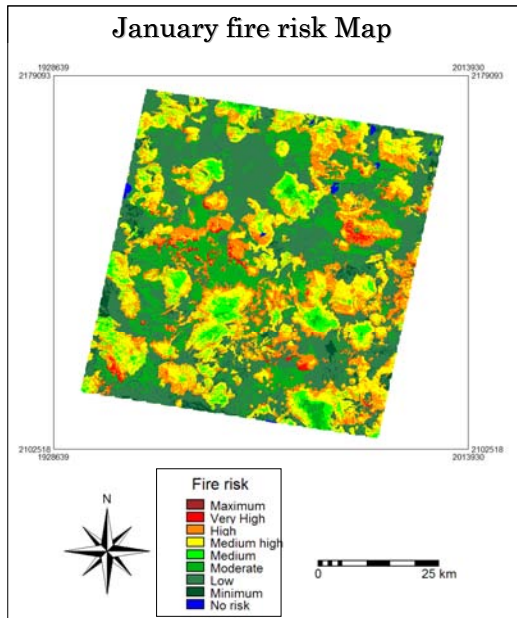


Unpaved road

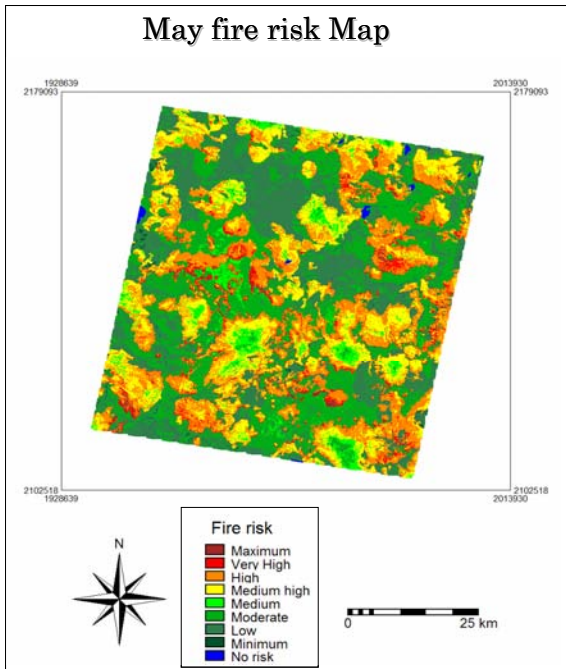


Path

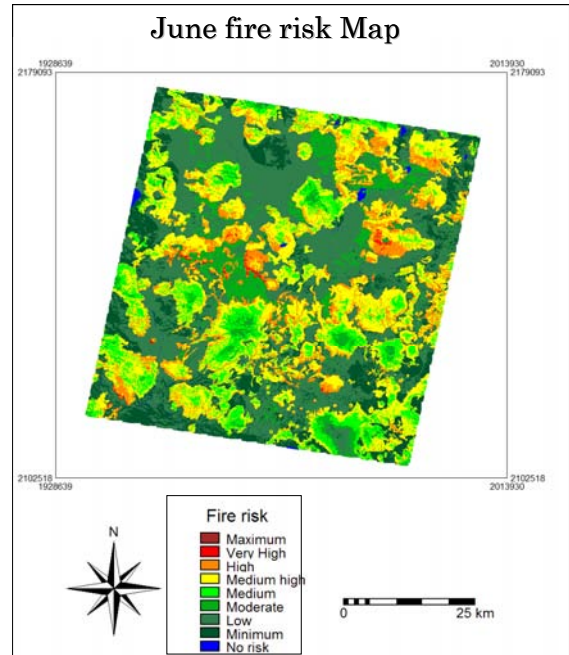
### 5.5. Weather sub-models



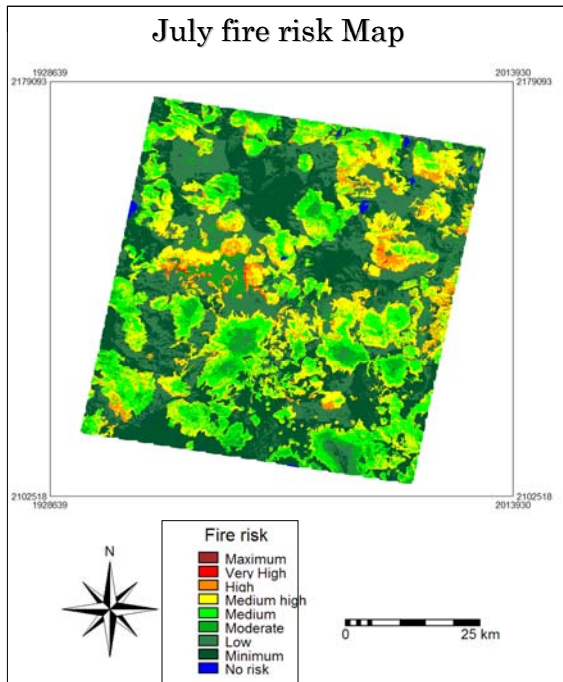
May fire risk Map



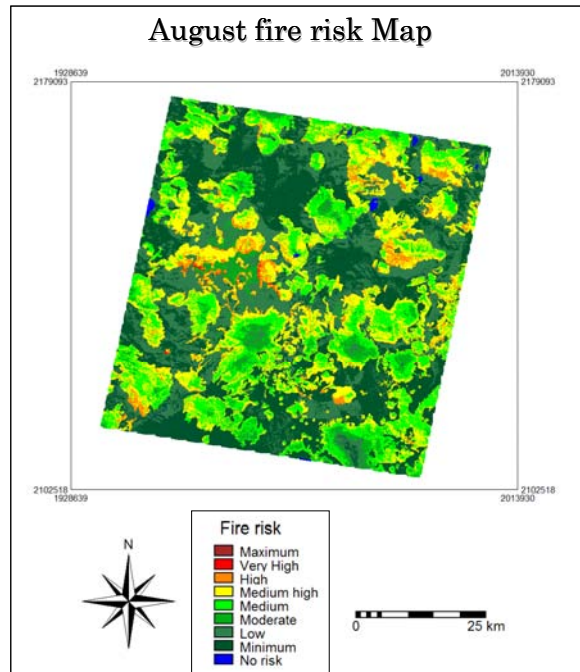
June fire risk Map

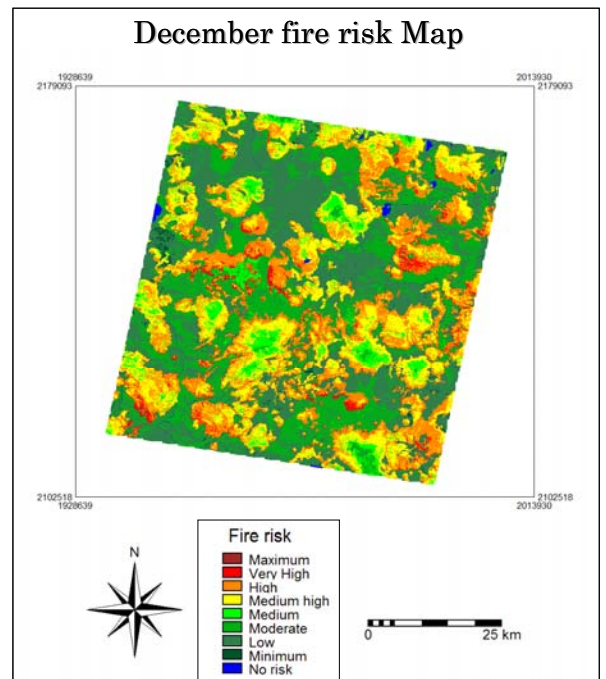
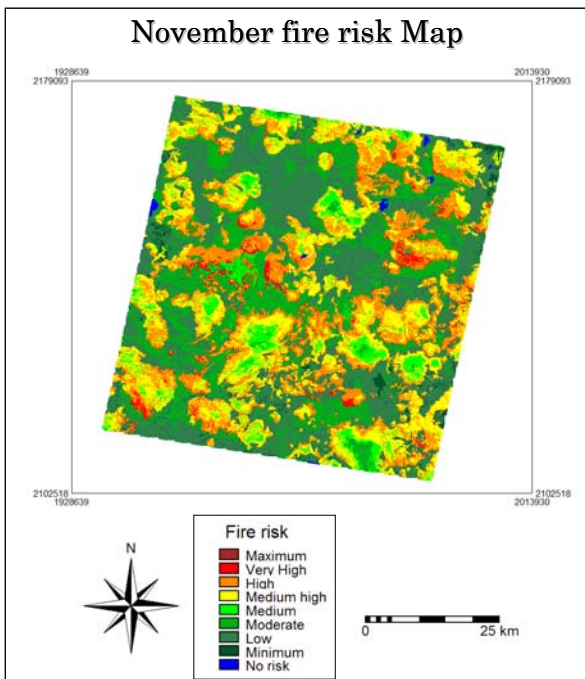
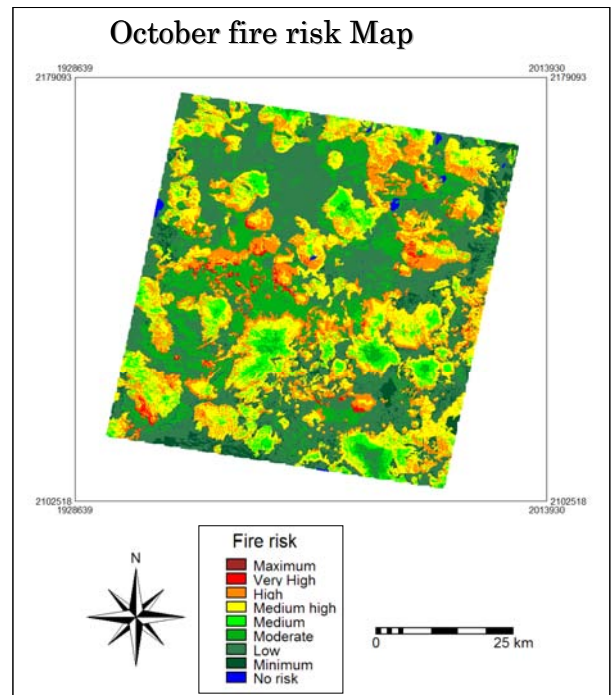
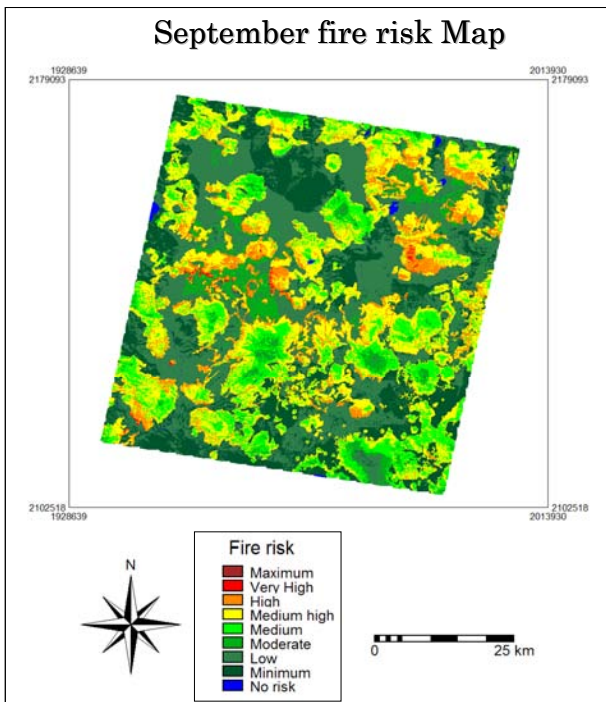


July fire risk Map



August fire risk Map





**Table 0-1. Burnt area (%) per fire risk category for the month of January**

January fire risk	Burnt Area (%)
Maximum to medium high	91.6
Medium to minimum	8.4

**Table 0-2. Burnt area (%) per fire risk category for the month of February**

February fire risk	Burnt Area (%)
Maximum to medium high	93.1
Medium to minimum	6.8

**Table 0-3. Burnt area (%) per fire risk category for the month of March**

March fire risk	Burnt Area (%)
Maximum to medium high	95.2
Medium to minimum	4.8

**Table 0-4. Burnt area (%) per fire risk category for the month of May**

May fire risk	Burnt Area (%)
Maximum to medium high	95.7
Medium to minimum	4.3

**Table 0-5. Burnt area (%) per fire risk category for the month of June**

June fire risk	Burnt Area (%)
Maximum to medium high	81.8
Medium to minimum	18.3

**Table 0-6. Burnt area (%) per fire risk category for the month of July**

July fire risk	Burnt Area (%)
Maximum to medium high	62.7
Medium to minimum	37.4

**Table 0-7. Burnt area (%) per fire risk category for the month of September**

September fire risk	Burnt Area (%)
Maximum to medium high	75.8
Medium to minimum	24.2

**Table 0-8. Burnt area (%) per fire risk category for the month of October**

October fire risk	Burnt Area (%)
Maximum to medium high	89.4
Medium to minimum	10.6

**Table 0-9. Burnt area (%) per risk category for the month of November**

November fire risk	Burnt Area (%)
Maximum to medium high	92.3

**Table 0-10. Burnt area (%) per fire risk category for the month of December**

December fire risk	Burnt Area (%)
Maximum to medium high	93.9