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ASSESSMENT OF FOREST FIRE RISK IN EUROPEAN MEDITERRANEAN REGION:

Comparison of satellite-derived and meteorological indices

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ABSTRACT

Forest fires are a major hazard to Mediterranean forests where, on average, half a million hectares of forested areas are burned every year. It is for this reason that the assessment of fire risk lies at the heart of fire prevention policies in the region. Often, the estimation of forest fire risk involves the integration of meteorological and other fuel-related variables leading to an index that assesses the different levels of risk. Two indices that are frequently used to estimate the level of fire risk are the Fire Weather Index (FWI) and the Normalized Difference Vegetation Index (NDVI). Although the correlation between the number of fires and the level of risk determined by the indices has been demonstrated; however the analysis that lead to this conclusion considered only the areas where the fires took place. The present paper analyzes the behaviour of these fire risk indices both in areas where fires took place and in those where fires did not occur. It analyzes and compares the potential of the two indices to discriminate different levels of fire risk over large areas using quantitative and graphical methods. The analysis is performed considering a dataset of 10 years of fire events, satellite data and meteorological data for Spain. The results show a better performance of the FWI over NDVI in identifying areas at risk of fires.

1 Introduction

1.1 Natural disasters and their prevention

During last years natural disasters have increased in the number of occurrences often showing the extreme force they could have. Earthquakes, floods, forest fires, hurricanes, tornados, avalanches, landslides and volcanoes are only some of the most known. Nevertheless, even if the increment of these occurrences produced huge amount of damages, on the other side it helped to draw the people attention. The economical damages derived as a consequence have no more been considered as the only effect. The ecological sensibility, growing everywhere, led to consider the wider set of involved conditions. It is now evident the possibility to prevent some of those disasters and to reduce their consequences commencing from daily behaviours. For example, the Kyoto protocol has been finally ratified with the aim to start reducing emission of greenhouse gases. Even though it has been proved that the terms fixed by the protocol are not enough to solve the problem of emissions, it demonstrates an initial will of the economical powers to change the actual condition. An observable tendency is to invest money, time and resources in the production of systems able to quickly react in presence of a disaster and, when necessary, able to "turn it off" more immediately as possible. Besides, these systems are studied to furnish a first help to people need it; to cure, to feed or to save them. Since it is not advisable to think to eliminate or stop events as earthquakes or hurricanes, the problem to solve is "how to reduce the consequences of a natural disaster". However, the answer to the question tends to consider events after their manifestation. Thus, the attention is drawn on how to react in order to reduce damages even though, frequently, the presence itself of a natural disaster implies instantaneous presence of damages. The alternative point of view in answering the question is to reduce the instantaneous damages. Understanding how to react in case of an event has to be analysed together with how to maintain the level of damages lower than possible; which means focussing the attention on prevention. Prevention that has not enough been considered since it is possible to judge useless an investment of money in trying to prevent a disaster which, effectively, could not occur. If money was invested for prevention of a natural disaster which do not occurred, these money would be reasonable considered as wasted. Thus, why invest money if is not strictly necessary? First of all because it is possible to demonstrate that the economical request subsequently a natural disaster abundantly overpass the request necessary for prevention. Moreover, because prevention itself does not imply injured people or died. Thus, the benefits produced by a good prevention scheme are undisputable even though, normally, they are identifiable in the long period.

1.2 Forest fires, a natural disaster for forest in Europe

Forest fire is a major natural disaster for the European territory. Also known as wildfires, vegetation fires or grass fires, it represents an uncontrolled fire in wildland. It is often caused by human careless or arson and, thus, it is one of the natural disasters more disposable to be prevented by a good preventive scheme.

The European Mediterranean region has been considered as one of the most important regions in the world for its outstanding biodiversity features. Thus, it should be of primary importance the increment in the efforts to cut down the about 400.000 hectares of forests and other wooded land annually destroyed by forest fires. On 1979, the European Community first recognised the problem of forest fire and, since that time, measures of forest protection have been applied by special Regulations. The aim of these Regulations regards the increment and development of activities co-ordinate at EU level to maintain, monitor and safeguard the forest ecosystem. Activities focussed on educating people to respect the environment and informing them on the risks and consequences of forest fire have been also developed. A step forward was done on 2002 with the introduction of maps of forest fire risk at European level. These maps represent the territory subdivided in different classes depending on the potential risk of forest fire. They propose a general condition of risk as well as its evolution for each of the European countries. This information is considered as the starting point for a large-scale prevention scheme. In fact, the estimation of the forest fire risk would help in identifying areas most prone to fire ignition and spread and to efficiently allocate forest fire fighting means and resources.

1.3 Study objective

A map of forest fire risk is the graphical representation of a collection of levels of risk obtained by an index of risk. An index of risk is made up by different variables combined in such a way to obtain particular values; which are referred to be as levels of risk. Nevertheless, the presence of a large group of variables to consider in the constitution of an index leads to the development of different indices of forest fire risk during the years. Each index has been developed and tested considering particular contexts and results obtained are considered reliable at local scale. Thus, a lack in analyses carried out on extended period of time and extended territories is noticeable. However, during last years, the problem of forest fires moved from a local problem to a more complex global problem. The European Commission extended the problem toward a community context in which not only the finances are shared by different countries, but also means and assistance. Consequently, the European Commission has incessantly introduced proper regulations and schemes of prevention in which a production of maps of forest fire risk is required.

At European level, the production of maps of forest fire risk at fine level of details could be considered too expensive either economically than in term of resources required. The indication of risk is daily extracted at national level and a resolution of few meters is difficult to manage and not fully relevant. In this work, indices of risk derived by remote sensing and meteorological data have been considered as a good compromise between availability and resolution. The introduction of remote sensing and the presence of a capillary network of weather stations permits, in fact, to have daily information over large-scale. Since the different nature of each index of risk a methods of index performances comparison is required in order to establish which index is best suitable to be adopted at European level.

The primary objective of the present study is to investigate the potential of indices of risk as a tool for the detection of forest fire risk at country level and their possibility to be extended at European level. At the moment, the production of maps of risk has been based on the extension of results obtained by local studies to the European level. Nevertheless, any study was performed to assess the real potential of a local index of risk to be applied to a global scale. Thus, this work presents results obtained by a retrospective analysis of long term time series of remote sensing and meteorological data in Spain; retained as an ideal starting point due to its extension and to its tendency to be subjected to forest fires.

1.4 Approach

Traditionally, an index of risk has been considered suitable if it presents some particulars behaviours. On one hand, the observed values must be show higher risk during the period of higher presence of fires. On the other hand, the observed fires have to occur in areas having higher values of risk. These requirements have been adopted in order to assess the performance of an index of risk. Nevertheless, limitations are observables. Both the analyses do not differentiate values of risk over burnt areas from values over non burned areas. Moreover, they do not allow direct comparison between results obtained by different indices. In this study, those limitations have been solved by the introduction of a qualitative and a statistical approach of analysis. In both the approaches the distribution of the values of the indices over burnt areas is compared to the distribution of indices values all over the territory. If the proposed indices are successful, then a statistical difference between the distributions should be observed; a more evident difference point out a better potential of a particular index of forest fire risk. Moreover, the performances of different indices have been converted in a numerical form which allows the comparison of results.

1.4.1 The indices of risk

Two different families of indices of forest fire risk have been investigated. Four indices of risk were derived by remote sensing data and one was derived by meteorological information. Due to their low spatial resolution, these indices permit a wide coverage at high temporal resolution and, consequently, have been retained suitable to be applied for the creation of daily maps of forest fire risk at extended scale. Their different nature permits to assess the rule that the vegetation status or the meteorological conditions plays in the assessment of forest fire risk.

The different nature of the considered indices, however, leads to a non direct possibility of comparison of the indices. Superficial analyses of the results could easily conduct to good potential for an index. The analysis of the trend of observed values and the analysis of the distribution of fire in the territory, for example, furnish information which could be use to classify the potential of an index. Nevertheless, they are not able to deeply investigate the real potential of an index. Besides, the process of reclassification of index values into classes of risk could highlights a not real high level of correlation between number of fires and classes of risk. To better focus these problems, following are reported as example the results obtainable using these analyses.

1.4.1.1 Average trend

The average trend would evaluate the potential of an index of forest fire risk by considering the average trend of the assumed values during the year. This simple analysis investigates the presence of high level of risk during the period of major presence of forest fire events. The following graphs reports the different behaviour for a remote sensing derived index, the Normalized Difference Vegetation Index, NDVI, (figure 1.1) and for a meteorological index, Fire weather Index, FWI, (figure 1.2) during the retained period considered by this work. They can not provide an indication of the real evolution of the values since only one value of a considered index in a considered day is reported. However, the general trend to assume values related to a higher level of risk during the summer period is noticeable.

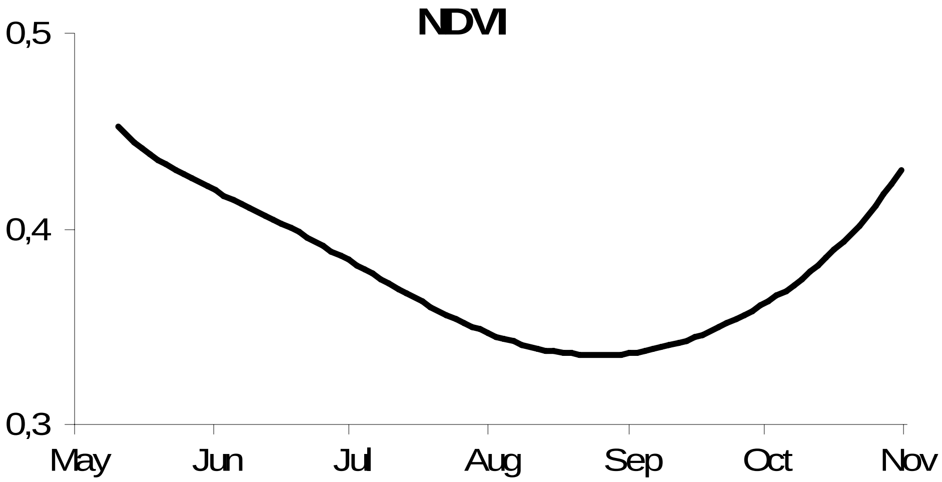

Figure 1.1: Average trend of NDVI values

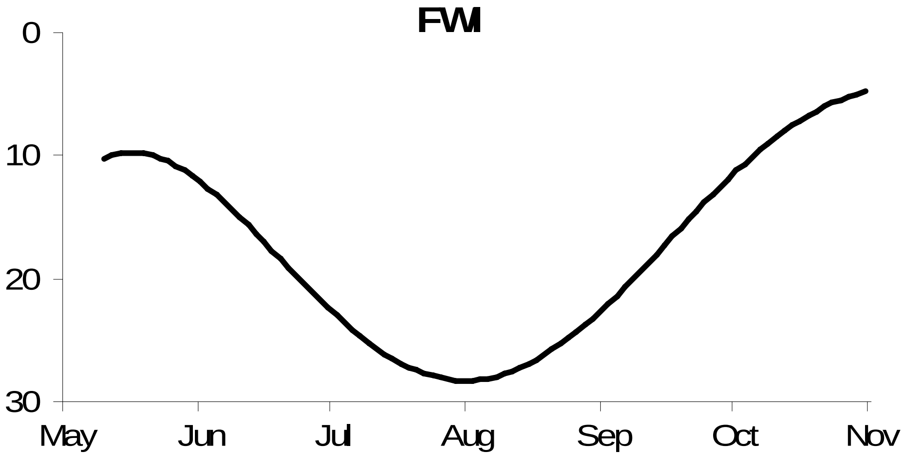

Figure 1.2: Average trend of FWI values

Thus, it is possible to observe how a considered index presents the tendency to assume highest levels of risk during the summer period, between July and September. This analysis could be considered as a graphical analysis in which it is possible to observe a correlation between levels of risk and period of major presence of forest fire occurrences. Nevertheless, no correlation between fire occurrences and index values could be derived. Moreover, there is no possibility to compare a graph of one index to the graph of another index to assess which one performs better.

1.4.1.2 Index re-classification

The index re-classification analysis would evaluate the potential of an index of forest fire risk observing the values of the index in presence of a fire occurrence. The hypothesis is that the goodness of an index of risk is valuable by considering relationship between number of fire events and values assumed by the index. Thus, an index would be judged reliable if most of the fires occurred when a high level of risk was pointed out by the index. Nevertheless, this analysis presents two problems. On one hand, it considers only values of the index over burnt areas. On the other hand, there are no rules to follow in order to exactly define how high level of risk should be represented by index values. The procedure most applied has been to study the events history and to classify the level of risk as a consequence of the observed information. The subdivision of the range of values assumed by an index into levels of risk is a consequence of the historical values of the index and thus strictly dependent by them. Following this simple procedure the observed values of the considered indices of risk were reclassified in six levels of risk; very low (f), low (e), moderate (d), high (c), very high (b) and extreme (a). The following graphs highlight how easy is to reclassify an index of fire risk in order to produce good results (figure 1.3). Each graph presents the number of fires which occurred for a particular value of the index of risk during the study period. The values placed more at left represents higher levels of risk meanwhile values placed more at right represents lower levels of risk. As explained, for each index it is possible to derive a consequential high value of square correlation coefficient. The square correlation coefficient was obtained by using an exponential model in order to fit the number of fires to values of the index. Nevertheless, these results are consequence of the procedure of reclassification; procedure that does not take into account of any other value of the index different from the one assumed during the fire. Thus, any procedure of comparison between different indices is difficult and not very reliable. For this reason, the potential of an index should be analysed by using directly the index values without introducing any process of reclassification.

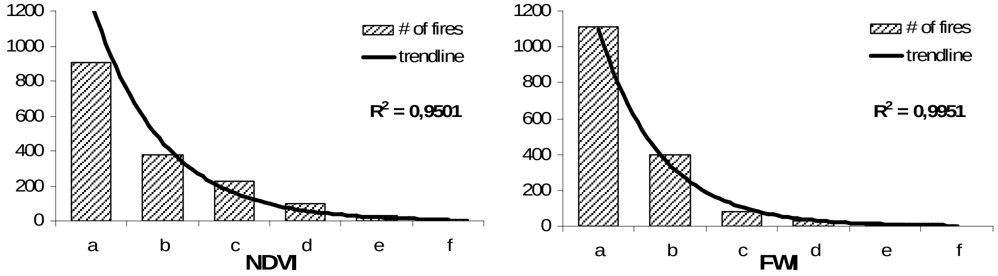

Figure 1.3: An example of an arbitrary index reclassification for NDVI and FWI values

1.4.1.3 Index context

These analyses present a problem of evaluation linked to the context of analysis. On one hand, the average analysis is carried out considering the entire territory and it does not discriminate burnt areas from other areas. On the other hand, the reclassification process is carried out considering only values of the index belonging to burnt areas with no comparison with other values of the territory. However, these problems are the main points in the process of evaluation of the performance of an index of forest fire risk in order to understand if an index is able to discriminate levels of risk in an extended territory. To better explain the problem an example built over the study data is reported.

The distribution of forest fires occurred in Spain in the year 2001 is shown by figure 1.4. The trend of the forest fires occurrence is immediately noticeable; higher number of fires during the summer period, lower number of fires during the others months. A comparison between the number of fires and the average behaviour of the indices values (see previous section) pointed out an existing relationship; a major number of fires tend to occur where a higher level of index risk is present.

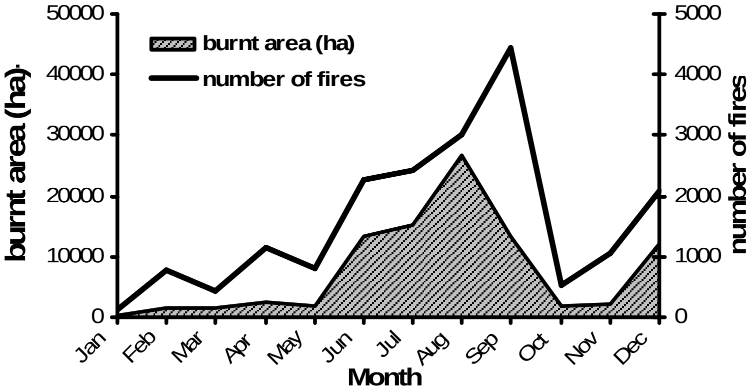

Figure 1.4: Distribution of forest fires and burnt area in Spain in the year 2001

Nevertheless, the presence of a high level of risk just the period before, or during, a fire occurrence it is a necessary but not a sufficient requirement in order to classify an index as a reliable index. In fact, if an entire territory was situated at the same level of risk at the same time, the indication furnished would be hardly useful. Figure 1.5 reports an example of high level of risk for the Granada region. Under those circumstances, if a fire occurred the index would produce good results. On the other hand, if the extension of the use of the same index to the entire territory produced an indication of risk as reported by figure 1.6, the index would furnish any added information more than the generally high level of risk for the entire territory. Consequently, it is not able to differentiate different areas in function of the risk status.

Figure 1.5: Levels of risk for the Granada region during a particular day

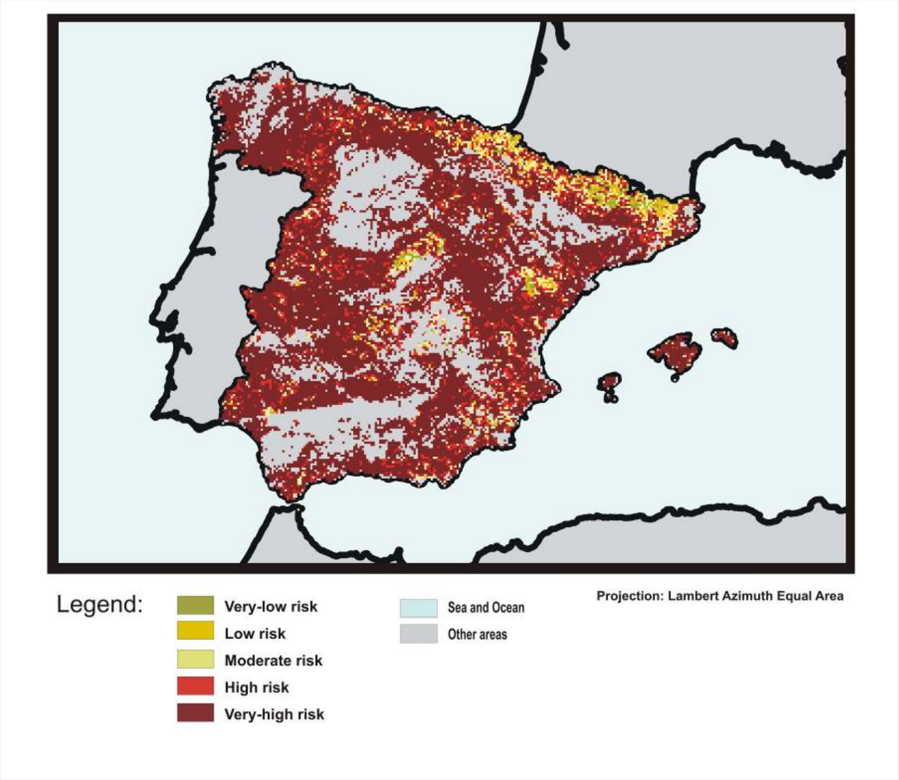

Figure 1.6: Levels of risk for the entire Spain during the same day as the previous

1.4.2 Qualitative analysis

The qualitative analysis adopted in this work permits to combine the two previous analyses. It compares the values of an index over burnt areas with the normal distribution of the values of that index. Thus, it analyses the values over burnt areas considering also values all over the territory. This analysis permits to verify the basis hypothesis that a fire tend to occur where a high level of risk is present. However, also this analysis does not permit an evaluation of the results more than the one furnished by a visual approach.

1.4.3 Statistical analysis

It has been deeply discussed regarding the importance to adopt a method of analysis of the indices able to assess the results numerically and independently by the adopted index the performance of this index. In the context of this work, the statistical approach estimates how much the information derived by the use of a particular index of risk could be better than the use of a random value. The introduction of the use of a random value in order to estimate the performance of an index permits the detachment of the obtained result from the index characteristics, as the range of values or the scale of reclassification and, thus, it permits a comparison of results obtained by different indices. This methodology evaluates day by day the value added in the estimate of fire risk given by a particular index.

Concluding, for the first time it has been possible to quantify the results obtainable by the use of different indices of risk in the forest fire assessment.

1.5 Structure

This research is divided by three sections. The first one introduces to the study context. The second describes the methodology of analysis and the third one presents the results and the discussions. Thus, the present chapter is followed by others three chapters focussed to the description of the field of study. The chapter "**Forest and the interaction with fire"** introduces to the definition of forest and fire and concludes with the description of the situation of forest fires in the European context. The chapter "**Forest fire risk assessment**" highlights the importance to assess risk of forest fire. It introduces the definition of forest fire risk and the variables that play role in fire ignition and propagation. It also introduces to the use of indices in order to evaluate the risk of forest fire. Meanwhile, the chapter "**Remote sensing applications"** introduces to the remote sensing science. It describes the advantages obtained by the introduction of remote sensing in forestry and concludes with a description of the NOAA polar orbiting environmental satellite series. The adopted methodology is presented in the chapter "**Data and Methods"**; in which are described the indices of risk utilised, the study area and the methods of analysis. The results obtained by each index and the comparative analysis are reported and discussed in chapter "**Results and Discussions"** and the last chapter "**Conclusions"** presents a final discussion of the obtained results analysing them with the objective of this work.

2 Forest and the interaction with fire

The term forest has not to be merely considered as a group of standing trees but has to be regarded as a complex ecosystem. This is essential to comprehend the behaviour and the relationship between forest and fire and it is at the basis of understanding the entire objective of the thesis. Accordingly, notions regarding forest and forest fire are presented together with an overview of the problem of forest fire in Europe. For each sub-chapter the general definition of the described term is followed by the definition suggested by the Forest Focus Regulation (European Commission 2003).

2.1 Forest

Forest: an ecosystem characterised by a more or less dense and extensive tree cover, often consisting of stands varying in characteristics such as species composition, structure, age class, and associated processes, and commonly including meadows, streams, fish, and wildlife – *note* forests include special kinds such as industrial forests, non industrial private forests, plantations, public forests, protection forests, and urban forests, as well as parks and wilderness (Helms 1998).

Forest: land with tree crown cover (or equivalent stocking level) of more than 10 % and area of more than 0.5 ha. The trees should be able to reach a minimum height of 5 m at maturity *in situ*. It may consist either of closed forest formations where trees of various storeys and undergrowth cover a high proportion of the ground, or of open forest formations with a continuous vegetation cover in which tree crown cover exceeds 10 %. Young natural stands and all plantations estab-

> lished for forestry purposes which have yet to reach a crown density of 10 % or tree height of 5 m are included under forest, as are areas normally forming part of the forest area which are temporarily unstocked as a result of human intervention or natural causes but which are expected to revert to forest. The definition of 'forest' includes: forest nurseries and seed orchards that constitute an integral part of the forest; forest roads, cleared tracts, firebreaks and other small open areas within the forest; forest in national parks, nature reserves and other protected areas such as those of special environmental, scientific, historical, cultural or spiritual interest; windbreaks and shelterbelts of trees with an area of more than 0.5 ha and a width of more than 20 m. Rubberwood plantations and cork oak stands are included. However, the definition of 'forest' excludes: land predominantly used for agricultural practices (European Commission 2003).

As explained by the general definition, forest is something more than a group of standing trees. It has to be considered as an ecosystem; a complex environment in which interaction and dependencies are largely present. However, since the most visible things in forest are trees, the first thought tends to relate forest to trees and to consider them as synonyms. Nevertheless, trees can not survive without the complex structure situated in their surrounding. Structure made up of different layers and interactions, as the substrate which contributes to furnish nutrition and moisture to the plants and the animals which feed on, shelter under, and benefit the plants; or the micro-organisms which exert direct and indirect effects on the plants and the atmosphere and climate which influence distribution, abundance, and productivity of all the organisms in the forest. In addition, there are also the plants interactions which exert mutual protection, competition, benefit and antagonism (Kimmins 2004).

It is important to understand the extension of forest, which cover about one third of the world's land area and which splendour is revealed in different varieties. World climates generate different forest ecosystems in which, temperature and humidity are the mainly responsible of the vegetation types. Forest extension is estimated in about 4.000 million of hectares located for the 47% in tropical zones, the 9% in sub tropics zones, the 11% in temperate zones and the 33% in boreal zones (FAO 2003). Moreover, forest is unevenly distributed across the continents: Europe, North and Central America, South America and Oceania (figure 2.1).

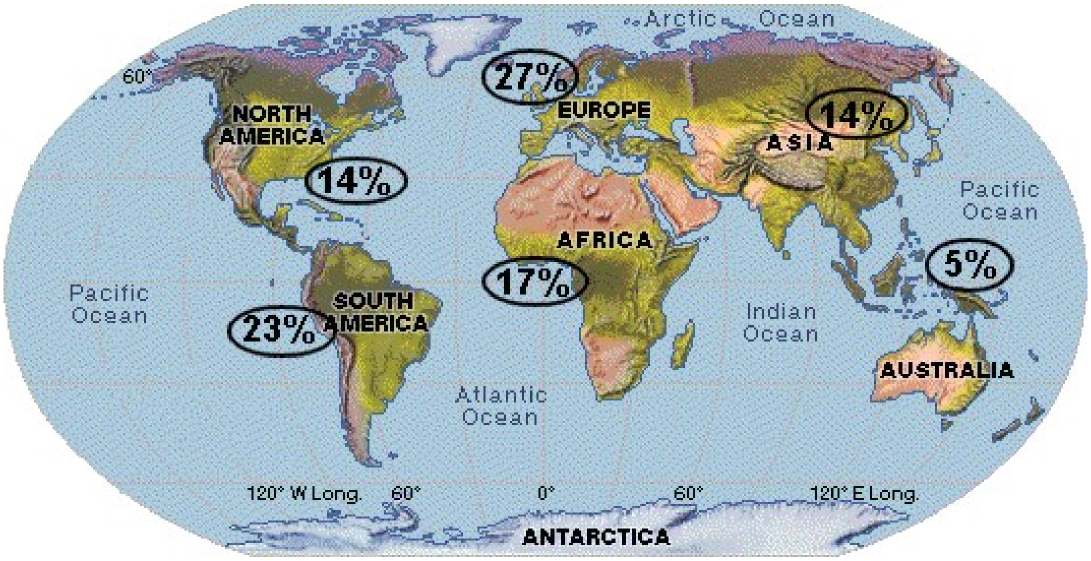

Figure 2.1: Forest distribution across the continents

2.1.1 Forest functions

Likewise the tendency to associate forest to trees, a study demonstrated how people often links the word forest to the idea of "green" and "fresh air" (Rametsteiner and Kraxner 2003). Nevertheless, forest also presents an added ecological, economic and social value. It could be helpful to avoid floods and erosion by retaining precipitation in the soil, acts as carbon sink and physical air filter and could furnish working and recreational places. A sample list of the most important forest's functions is reported in the following tables (table 2.1) (European Parliament 1997).

Table 2.1: Sample list of the most important forest's functions

Ecological functions	
REGULATION functions	
CLIMATE	
Temperature	• moderating role (albedo, evapotranspiration, etc.)
Humidity	• moderating role (evapotranspiration, etc.)
Atmospheric composition	• buffer role (carbon cycle, etc.)
Rainfall	• stimulates precipitation (increases rain fall volume, humidity, rough surface, fog condensation, etc.)
Wind	• protects against wind action (hedges protect fields and buildings, mixed woodland and pasture protect microclimates, roughness slows wind speed down, stabilises dunes, etc.)
AIR QUALITY	
Refinement	• fixes pollutants, recycling
Purification	• diffuses essences and volatile components
WATER SYSTEMS	
Controlling rising water levels	• reduces surface runoff, increases concentration time in mountain basins
Maintenance of low levels	• infiltration of excessive rainfall, water reserves, etc.
WATER QUALITY	
Purification	• fixes pollutants, recycling
Protecting water-catchments and supply areas	• reduction of sources of pollution
Reduction of sediment content in water flows	
SOIL MAINTENANCE	
Reduction of diffuse erosion	• protects from the impact of rain, soil stabilisation
Reduction of erosion in fragile areas	• physical protection, reduces surface runoff
Soil reconstitution	
PROTECTION functions	
AGAINST NATURAL RISKS	• torrential and sudden rises in water levels, avalanches, land slides and falling rock
AGAINST NOISE	• filtering effect
PRESERVATION functions	
BIOLOGICAL DIVERSITY	
Maintenance of current diversity	• provides conservation at all levels (genetic, species and habitat diversity)
Preservation of future diversity at the local level	• preserves evolution potential • maintains liaisons and corridors
Preservation of future diversity in land-use planning	• provides dynamic conservation by linking up forest areas into a network

Economic functions	
PRODUCTION function	
WOOD	
Industrial wood	• material support for other functions • wood for building and industry • industrially processed wood products: sawnwood, furniture, joinery pieces, frames, panels, paper and paperboard, etc.
Fuel wood	• industrial use • domestic use (heating and cooking)
OTHER RAW MATERIALS	
Wood-derived chemicals	• essences, resins, food flavourings (strawberry, liquorice) • various chemical substances • tannin, latex • organoleptic substances used in oenology (barrel production)
Other chemicals derived from the ecosystem	• aromatic and medicinal plants • molecules used in food and pharmaceutical processing
Game fowl	• source of food • source of leisure and hunting activities
Cork and bark	• isolation, cork stoppers, tannins, etc.
Decorative plants	• production of specific plants: Christmas trees, branches • remains from clearing and pruning • direct forest supply (boxwood, holly, foam, etc.)
Other non-wood products	• gathering for domestic or commercial use (mushrooms, small fruit, chestnuts, honey, seasonal flowers, etc.)
ACTIVITIES and SERVICES	
Environment for recreation and providing nourishment	• wild plant life • domestic plant life: specific cultivation systems, grazing
Reserve of land	• agricultural and mining resources (tropical forests) • urbanisation, and access routes
Hunting	• hunting rights • remunerated activities (see *Social functions*, recreational functions)
Leisure activities and tourism	• source of employment • maintains rural activities
Land use planning	• creation of rural infrastructure networks

<table>
<tr><th colspan="2">Social functions</th></tr>
<tr><th colspan="2">LANDSCAPE function</th></tr>
<tr><td><i>Rural landscape</i>
<i>Urban landscape (trees and green areas)</i></td><td>• landscape design: opening, closing, density and volume, etc.
• artificial landscape embellishment function</td></tr>
<tr><th colspan="2">RECREATIONAL function</th></tr>
<tr><td><i>Leisure-relaxation</i>
<i>Leisure-sports</i>
<i>Leisure-culture</i>
<i>Eco-tourism</i></td><td>• using specific visitor reception facilities or not
• search for peace and quiet, fresh air, getting away and freedom - the <i>anti-city</i> approach
• sports activities with or without equipment
• hunting, fishing
• discovering natural environments
• artistic activities: photography, painting, etc.</td></tr>
<tr><th colspan="2">EDUCATIONAL function</th></tr>
<tr><td><i>Information - sensitising</i>
<i>Eco-citizenship education</i></td><td>for everyone, through:
• contact between foresters and the public
• organisation of events (guided visits, day-long initiation programmes, etc.)
for children, through:
• educational visits to the forest
• incorporation of the forest theme into educational programmes
• co-operation between foresters and educators</td></tr>
<tr><th colspan="2">CULTURAL function</th></tr>
<tr><td><i>History</i>
<i>Myths</i>
<i>Aesthetic and spiritual values</i></td><td>• create a forest-society link throughout generations
• protection of archaeological remains and historical monuments
• temporal record of different forest events: dendrochronology, anthracology, palynology, etc.
• symbolism
• imagery
• aesthetics: the landscape, artistic inspiration (music, painting, etc.) and literature
• initiatory</td></tr>
<tr><th colspan="2">STRICT SENSE SOCIAL function</th></tr>
<tr><td><i>Standard of living of populations</i>
<i>Land use planning</i></td><td>• see <i>Economic function</i>, activities and services</td></tr>
</table>

2.1.2 Forest in Europe

The European territory is covered by about 1.000 million hectares of forest which present a proportion with land area of 47%. Consequently, almost half of Europe could be considered as forested. This territory has been classified in nine bio-geographical regions: Alpine, Artic, Atlantic, Black sea, Boreal, Continental, Mediterranean, Pannonian and Steppic (figure 2.2). In these regions the main categories of forest are: Western Taiga, Oak and Beech forests, Deciduous Mediterranean forests, Sclerophyllous Mediterranean forests, Temperate mountain conifer forests, Mediterranean and Macaronesian mountain conifer forests (European Commission 2003).

The WWF identified the Mediterranean region as one of the most important regions in the world because of its outstanding biodiversity features. Mediterranean forests, situated in a transitional zone between the European, African and Asian continents, are one of the world's centres of amazing plant and faunal diversity, containing 25.000 floral species which correspond to the 10% of the world's flowering plants on just over the 1.6% of the Earth's surface.

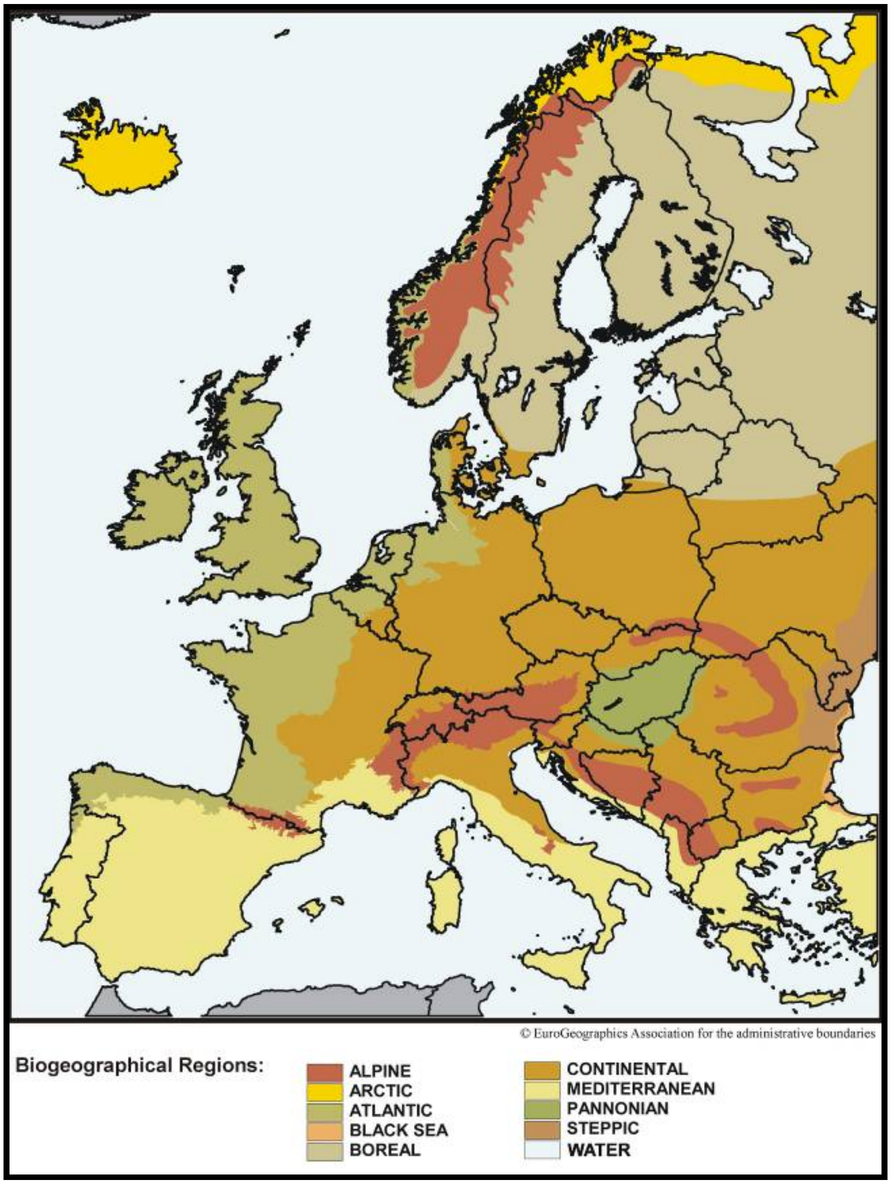

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Figure 2.2: Biogeographical distribution of the European territory

2.2 Fire

Fire: rapid burning of combustible material with the evolution of heat and usually accompanied by flame (Encyclopædia Britannica 2005).

Together with air, earth and water was considered as one out of four elements that, in ancient and medieval cosmology, constituted the physical universe. Initially originated by lightning, it quickly became an essential tool for the human race. Indispensably to keep warm and cook the food, it was adopted also in hunting animals and to clear forests of underbrush. Fire is an ecological factor of extraordinary power. It is able to transform the environment and to influence the structure, the composition and the richness of the vegetation. It could assume uneven vigour and frequency.

2.3 Forest fire

Forest fire: a fire burning uncontrolled on lands covered wholly or in part by timber, brush, grass, grain, or other inflammable vegetation (FAO 1986).

Wildfire, wildland fire: any fire occurring on wildland expect a fire under prescription (FAO 1986).

Forest fire: fire which breaks out and spreads on forest and other wooded land or which breaks out on other land and spreads to forest and other wooded land. The definition of ‘forest fire’ excludes: prescribed or controlled burning, usually with the aim of reducing or eliminating the quantity of accumulated fuel on the ground (European Commission 2003).

During the last years, uncontrolled forest fires produced a huge amount of damages both environmental and economical. For this reason, the term forest fire has been referred to as a natural hazard. In particular, it has been referred to as a major hazard for the European forests (San Miguel-Ayanz et al. 2000). However, conclusion could not be generalised since forest fires are part of the nature cycle and have always occurred. Prescribed natural fires are fundamental in order to preserve the natural role of fire in the ecosystem. They contribute to create new niches for fauna and flora and help to fertilise the soil. However, the strong tensions in landscape use and management, the high densities of population in the suburban and tourist areas together with rural abandonment have modified the incidence of fire. As a result, fire has progressively become a consequence of human behaviour (European Commission 2001).

Differently to prescribed natural fire, for wildfires a suppression action is necessary. Because of their nature, these fires introduced unexpected changes in the forest ecosystem. They are able to alter the natural cycle in a fire prone area with a resulting aggravation of the consequent effects. Thus, fire could be considered as a paradox. It destroys plants and animals causing extensive ecological damage but, at the same time, it is the source of forest regeneration and nutrient recycling (Rowell and Moore 2003).

2.3.1 Fuel

Fuel: the combustible organic material in forests and other vegetation types as grass, branches and wood, including agricultural systems which can be consumed by fire. A fuel type is any identifiable association of fuel elements of distinctive species, form, size, arrangement or other characteristics that will cause a predictable rate of fire spread or difficulty of control under specified weather conditions (FAO 1986).

Some proprieties of the fuel, like size and shape, compactness and moisture, play an important role in the fire ignition and spread. It is known that small fuels ignite and sustain combustion easier than large piece of fuel; since less heat is required to remove fuel moisture and raise a small particle to ignition temperature. Also compactness influences the spread rate; slower spread rates occur if fuels are compacted whereas loosely compacted fuels normally react faster to moisture changes and have more oxygen available for combustion. The amount of fuel that is available for combustion in a given fire is determined largely by the amount of water in the fuel; referred to as fuel moisture. When the moisture content is high, fires have difficult to ignite, and burn poorly if at all. With little moisture in fuel, fire starts easily, and wind and other driving forces, may cause rapid spread at high intensity. (Johnson and Miyanishi 2001).

2.3.2 Combustion

The combustion process involves chemistry, physics and fluid mechanics. When fire burns through wildland fuel, the process is affected by a multitude of factors including turbulence and no uniformity. The fire triangle has been used to describe the interacting factors involved in fire fundamentals (figure 2.3). Fuels burn under appropriate conditions, reacting with oxygen from the air, generating combustion products and releasing heat. If the triangle is broken the fire goes out. Fire is strictly dependent by three parameters: fuel, oxygen and heat. Each of those is necessary to avoid the triangle break and permit the fire to ignite (Pyne et al. 1996).

Figure 2.3: The fire triangle model

2.3.3 Fire types

A forest fire could occur and evolve assuming different characteristics. Consequently, different types of forest fire have been classified (figure 2.4). The most familiar fire type is the surface fire. It represents the most common propagation regime and consists in rapidly burning fire that sweep quickly over an area, consuming litter and the aboveground portions of herbs, shrubs, grasses and lower branches of trees. If conditions are favourable a surface fire may extend to the upper layers of the crown foliage. A fire affecting mainly the crowns of the woody vegetation is called crown fire. Frequently, it leaves most of the steam and the forest floor relatively untouched and is difficult to control since strictly dependent to wind conditions. Moreover, a fire could evolve below the terrain. Referred to as ground fire, it consists principally in largely flameless fire that burn slowly through thick surface accumulation of organic matter, duff and roots and it is very difficult to detect and control. In some particular conditions a ground fire can became a flaming surface fire if not adequately treated (Viegas 2002). Furthermore, more the one form of fire could take place at the same time (i.e. a crown fire could be accompanied by a ground fire).

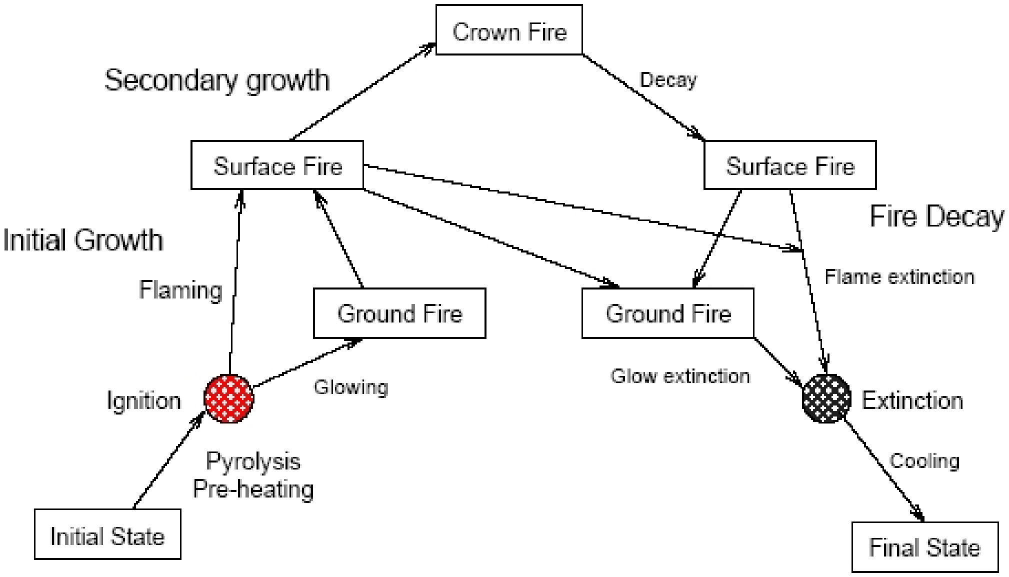

Figure 2.4: Fire growth, spread and decay from (Viegas 2002)

2.3.4 Effects

The evaluation of the effects of a fire a priori is not always possible because the consequences of a forest fire depend by several aspects. Climate conditions, terrain topography, intensity and permanence of the fire are the prevailing elements.

Wind condition influences the fire behaviour and is really hard to predict. It depends by topography, vegetation and local heating and cooling. Besides, topography may cause dramatic changes in fire behaviour as a fire progress over the terrain. In addition, the fire itself may influence the environment and thus the fire behaviour; heating from the fire can modify or produce local winds contributing to atmospheric instability and causing cloud development.

The effects of fire on soil vary with the proprieties of fuel, fire and soil itself. The consequences are physical, biochemical and biological as well as economic. Fire is able to influence soil temperature, soil structure and the ability of the soil to absorb and store water (Pyne et al. 1996). Forest fires produce gaseous and particle emissions that impact the composition and functioning of the global atmosphere. They are a source of carbon emitted into the atmosphere which influences climate change but are also an irreplaceable sink of carbon. For this reason, the Kyoto protocol, on article 2.ii, suggests the improvement of sustainable forest management practices, afforestation and reforestation.

2.3.5 Fire management

Since the forest is an ecosystem, the maintenance of the forest is vital not only for the tree itself, but also for the sustainability of the others forms of life. Forest is a provider of environmental services. It protects the soil from desertification and avalanches, furnishes a natural barrier against wind, attracts tourist increasing tourism and plays an important role in the livelihoods of poor people. Therefore, the reasons to protect forests from fire, pollution and other possible damages are obvious; forests and their structural and biological diversity are an important part of the natural environment.

For this reason, several legislations evidenced that forest constitutes a most important renewable resource available and encourage a constant support to researches on forest ecosystems and to education and training on forestry. The strong importance of forests and forestry policy has been considered by all the European member states.

An accurate analysis of the relationship between man and forest is essential to assess fire incidence, ignition and management. As already said, man is considered as a primary responsible of forest fire occurrences and this should be considered at the basis of any fire management planning.

A balanced fire management system is made up of different elements; prevention, preparedness, suppression and recovery. Each element is equally important and directly relate to the others.

The prevention and preparedness scheme evaluates the vulnerability of the territory to fire. Critical periods and areas on where forest fires could be stronger are evaluated not only using experience but also through tools like GIS mapping. Areas at higher fire risk should be subjected to specific actions of preventive measures of land-use planning, i.e. fuel arrangement can be altered for hazard reduction.

The suppression scheme would efficiently allocate and use the forest fire fighting means and resources. In order to handle the fire at the initial stage and consequently minimize the potential damages.

The recovery scheme regards the restoration and the care of areas after fire occurrences.

A fire management system should be considered as an integral part of the landscape planning in all the areas at high risk from forest fires. Moreover, a fire management policy will be more effective only if most of the resources and efforts are employed at the early stage of the fire fighting chain: the prevention (WWF 2003).

2.4 European condition

Every year, an average of 40.000 fires destroys about 400.000 hectares of forests and other wooded land in Europe, causing huge economic, social and environmental damages. Figure 2.5 presents the evolution of the problem from year 1980 to year 2002. It shows the total number of fires against the total burnt area in the EU Mediterranean region (European Commission 2004).

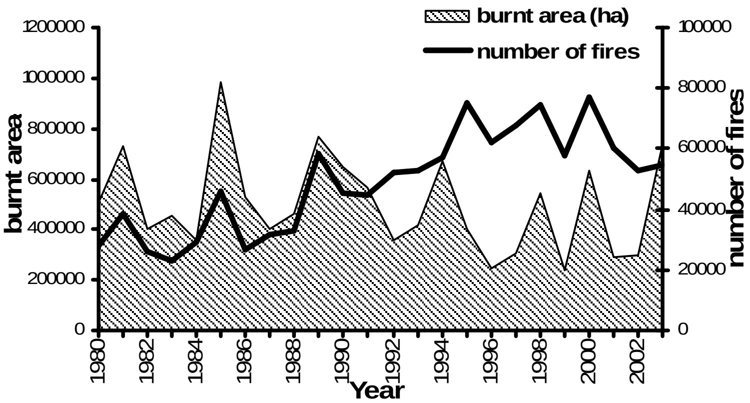

Figure 2.5: Burnt area (ha) and number of fire evolution in the EU Mediterranean region

If we assumed fires as a phenomenon equally distributed during the year, the previous data would imply about 100 fires and 1.000 hectares of burnt forest each day. Furthermore, if we reduce the analysis only to the fire campaign period (from May to October), the number of fires and the amount of burnt area up to more than 200 and more than 2.000 ha, respectively. Only during 2003 in Spain, forest fires affected about 149.000 ha of territory. The Ministerio de Medio Ambiente estimated on 405.570.000 euros the consequent economical loss, primary product plus environmental benefit (Ministerio de Medio Ambiente 2004). Estimation that did not take into account further people injured or died and damages to private properties. In Europe, forest fires are mainly caused by negligence or pasture burning and very few still remained naturals (figure 2.6) (Velez and Merida 2002). This situation is further aggravated by inadequate or ineffectively applied laws and administrative tools; which should punish the responsible for forest fires and ensure the recovery of damaged areas. These figures underline the entity of the problem.

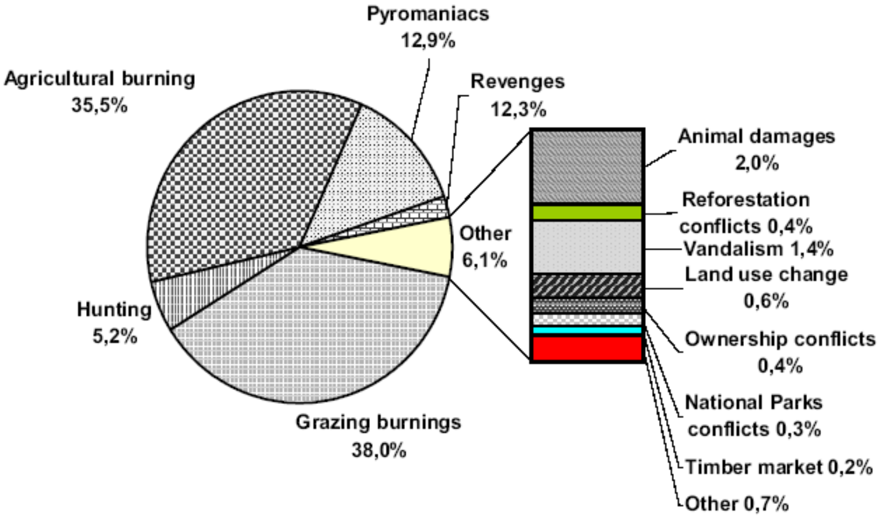

Figure 2.6: Reasons of arson fires (source Velez and Merida 2002)

The European area most affected by the problem of forest fire is the Mediterranean basin. The European Mediterranean basin is characterised by hot and dry summers, cool and wet winters, and long and intense human impact. Meanwhile abandoned land in the northern European countries is increasing at the expense of marginal agriculture; in the southern areas of western Mediterranean growing populations are reducing forests and shrublands by overgrazing and extending arable lands. This conditions lead the European Mediterranean Basin quite prone to wildland fire and differentiate it from the northern part of Europe (Pausas and Vallejo 1999). As a consequence, fires are not equally distributed along the European territory in which the Mediterranean basin results most affected by the problem. In particular, northern territory of Portugal, Spain and southern part of Italy are the more prone. Generally, they present a high average of fire occurrences every year and are the mainly responsible of the bigger part of the burnt area amount (figure 2.7) (European Commission 2004).

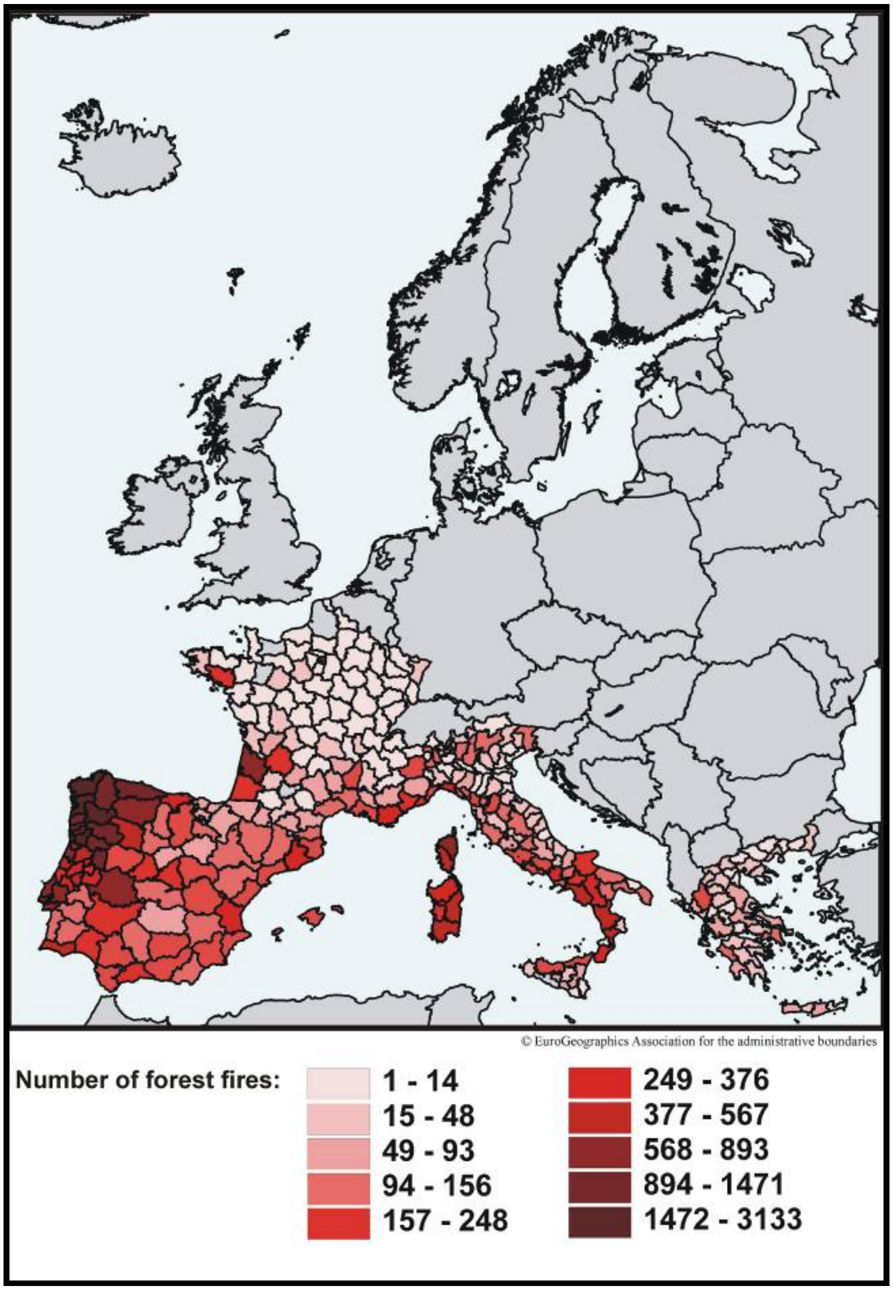
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Figure 2.7: Yearly average number of fires in the Mediterranean region

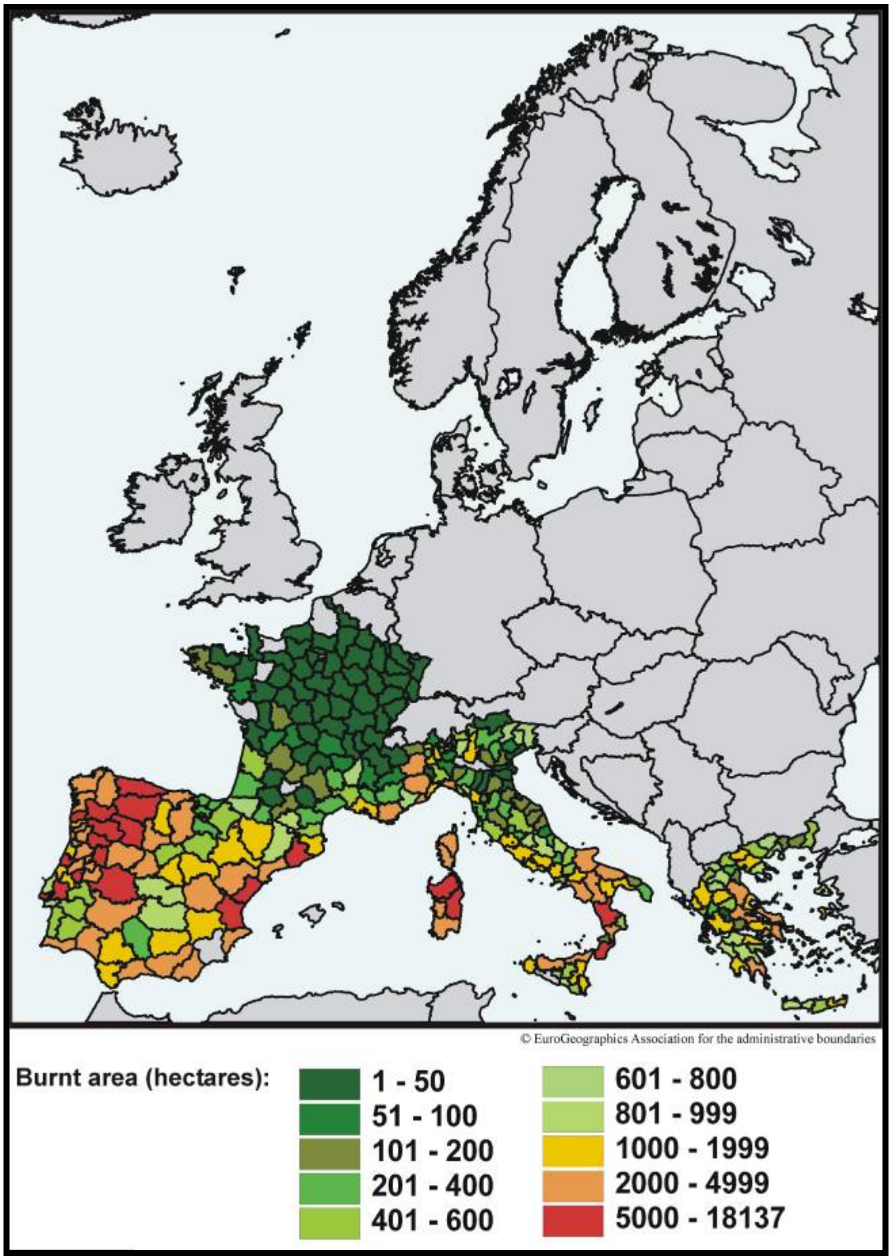
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Figure 2.8: Yearly average burnt area (ha) in the Mediterranean region

The Community started to make a financial contribution to implement measures to protect forests against fire since year 1979. Regulation (EEC) No 3529/86 (European Economic Community 1986) was the first Regulation adopted by the Council to ensure co-financing of measures to protect forest against fire. Following this Regulation, a Community scheme to increase and develop activities co-ordinate at EU level was established by Council Regulation No 2158/92 of 23 July 1992 (European Economic Community 2003, Poggi et al. 2004). The scheme aimed to provide increased protection for forests, in particular to step up efforts undertaken to maintain and monitor forest ecosystems and to safeguard the various functions which forests fulfil for the benefit of rural areas.

In particular, the EU financial contribution is focussed on the following measures:

- Studies to identify the causes of fires and to formulate proposal to eliminate such causes;
- Campaigns to inform and educate the public on the risks and consequences of forest fires;
- Set up and improve systems of prevention, with particular emphasis on the launching of protective infrastructures such as forest paths, tracks, water supply points, firebreaks, and preventive forestry measures within the framework of a global strategy for the protection of forested land against fire;
- Set up and improve forest monitoring systems (European Commission 2003).

According to Article2 of Regulation (EEC) No 2158/92 each Member State provided a list of areas classified by degree of risk. It was classified as high risk area an area in which the risk of forest fire presents a serious threat to the ecological balance and the safety of people or goods. Medium risk areas were those in which the risk of forest fire is a significant threat to forest ecosystems but is neither permanent nor cyclical. Remains areas where classified as low risk areas. The resulting risk map is presented in figure 2.8.

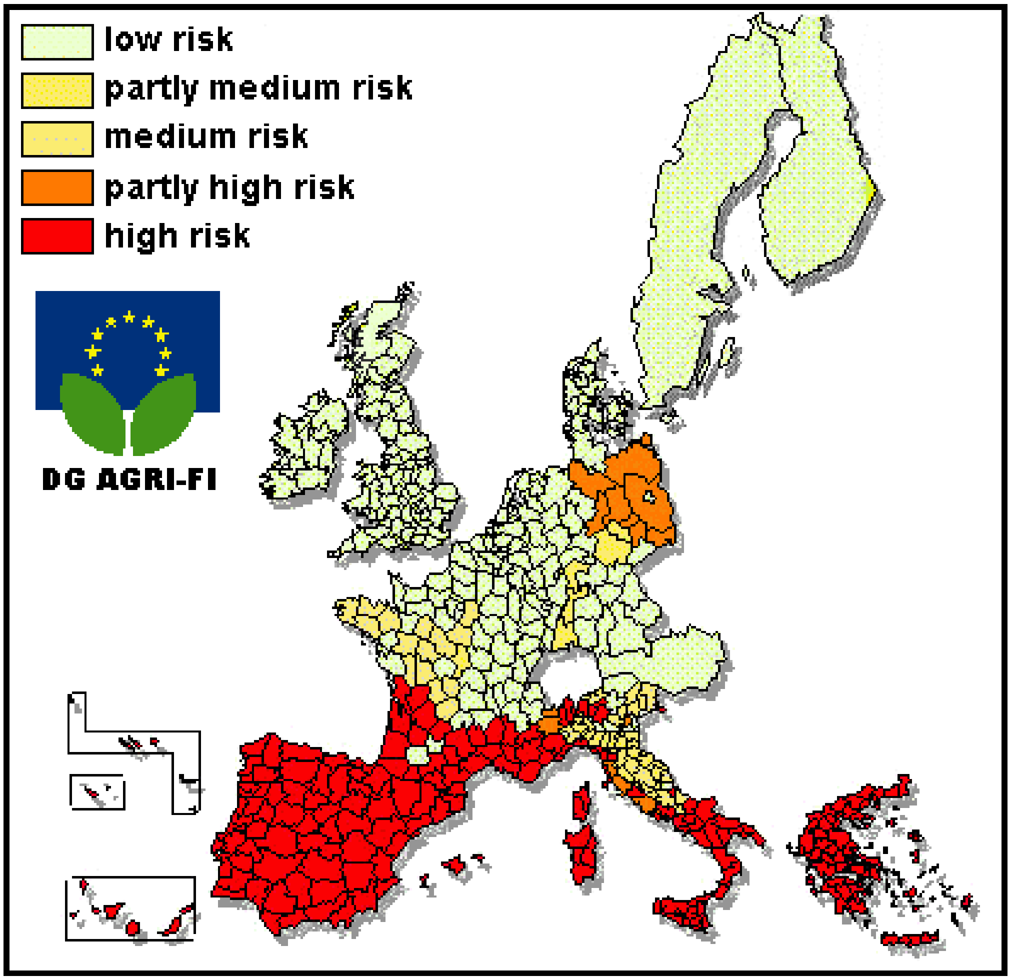


Figure 2.9: Classification of the territories of the Member States according to the degree of forest fire risk (source DG AGRI – FI).

3 Forest Fire Risk Assessment

Fire danger: "the resultant, often expressed as an index, of both constant and variable factors affecting the inception, spread, and difficulty of control of fires and the damage they cause"

Fire hazard: "a measure of that part of the fire danger contributed by fuels available for burning"

Fire risk: "(1) the chance of fire starting as determined by the presence and activity of causative agents, (2) a causative agent, (3) a number related to the potential of firebrands to which a given area will be exposed during the rated day" (FAO 1986)

The terms danger, hazard and risk have been often used in an inconsistent and confusing way in wildland fire's literature. They are used without a clear agreement among different specialists, countries and language tradition (Chuvieco et al. 2003). This lack of clear definitions could easy become an obstacle to risk research and management. A rigorous analysis has to be supported by a clear terminology in order to make results understandable and shareable throughout the wildland fire community.

In this context, Bachmann achieved a research (Bachmann and Allgöwer 2001) in which he suggested the term "fire danger" as useless for fire research because referred to an abstract concept based on personal opinions. He described the term as defined by subjective human and societal perceptions and assessments of events and outcomes that are considered harmful. Besides he defined the term "fire hazard" as a synonym for the process of wildland fire itself. Thus, he concluded suggesting as central term for wildland fire the term "fire risk"; since it takes account of the probability of a wildland fire to occur at a specified location and under specific circumstances, together with its expected effects. A precise definition of the term "fire risk" for forest fire related researches was also defined by FAO (FAO 1986).

The fire risk requires identifying potentially contributing variables, referred to as causative agents, to be assessed. However, likewise for the definition also the assessment of the risk presents different meaning in different countries. Traditionally, forest fire risk has been computed at national level or local scales using different variables and approaches. Thus, the different data sources and methodologies involved leading to indices not immediately inter-comparables (San-Miguel-Ayanz et al. 2003).

This chapter analyses the principal variables involved in the forest fire risk assessment and concludes with a brief description of some of the currently used indices of forest fire risk estimation.

3.1 Variables involved

Several are the potentially contributing variables for forest fire risk assessment as several are the methods to regroup them. A possible way of collection is based on the time variability. There are variables changing value almost continuously during the day and variables having a variation noticeable only over a long period of time; week, month or even years. Respectively, these variables were classified as short-term variables and long-term variables. Evapotranspiration, relative humidity, wind and air temperature furnish an example of variables clearly unsteady during the day. Fuel type, fire history, amount of population, topography of the territory, soil type and proximity of roads are variables with a roughly stable behaviour in a short period (figure 3.1).

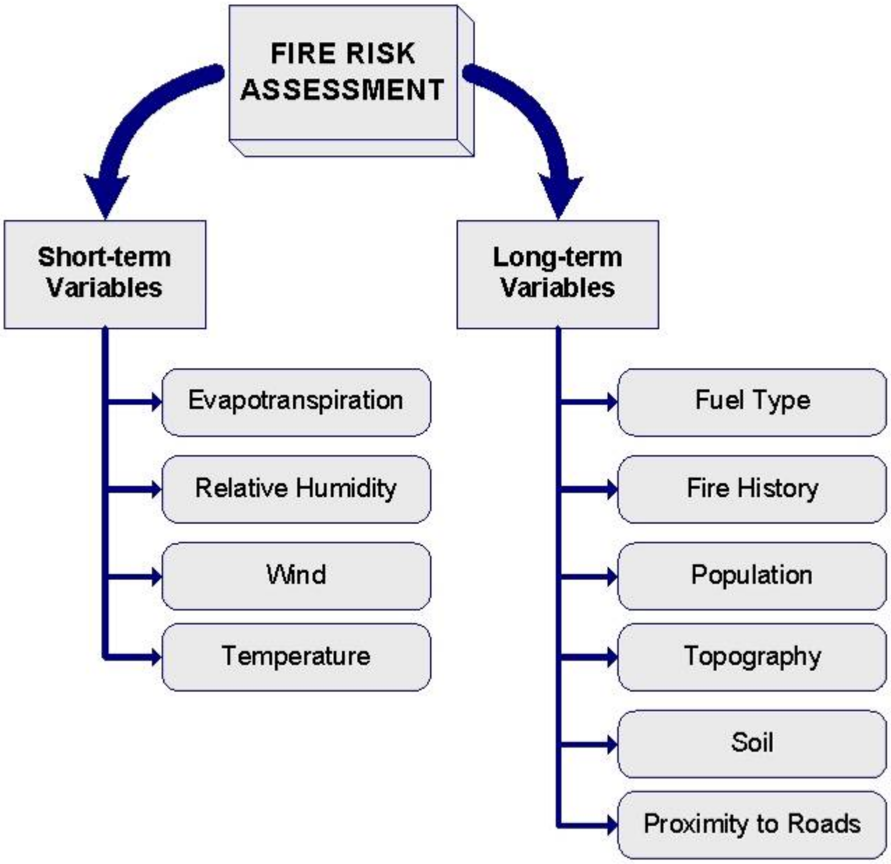


Figure 3.1: Potentially contributing variables for forest fire risk assessment

Alternatively, another possible manner to collect contributing variables is considering their nature. Variables could depend by meteorological conditions, vegetation condition or by human behaviour as described in the follow chapters.

3.1.1 Meteorological-related variables

Fire occurrences and propagation are strongly related to particular meteorological conditions. Solar radiation, air temperature, relative humidity, precipitation, wind (average speed, turbulence intensity and direction) and vertical structure of the atmosphere are the mainly meteorological variables involved (Viegas 1998). Each of these variables plays a relevant role; even though, the consequential high variability they present, makes difficult their management.

3.1.2 Vegetation-related variables

The understanding of water retention in plants and in soil is basic to predict moisture content of vegetation; which plays an important role in fire ignition and propagation. If meteorological conditions are ignored, the most significant factors affecting the amount of water held and transported in the vegetation are their chemical composition, internal structure and physical proprieties. This connection is better comprehensible by examining the leaf structure at a rather fine level of detail (figure 3.2).

The amount of moisture held in the cell walls of fuel particles is related to composition and crystalline structure of the walls, whereas the liquid water held in the cell cavities is determined by the larger scale capillary structure. The loss of moisture from the interior of the leaf is prevented by a translucent waxy layer, the cuticle. The pigment chiefly responsible for the green colour the characterised living vegetation is the chlorophyll. Light passing through the upper tissues of the leaf is received by chlorophyll molecules in the palisade layer, specialised for photosynthesis; process by which plant cells produce usable chemical energy through solar energy. The photosynthesis activity together with the moisture content has been used as possible indicators of vegetation status.

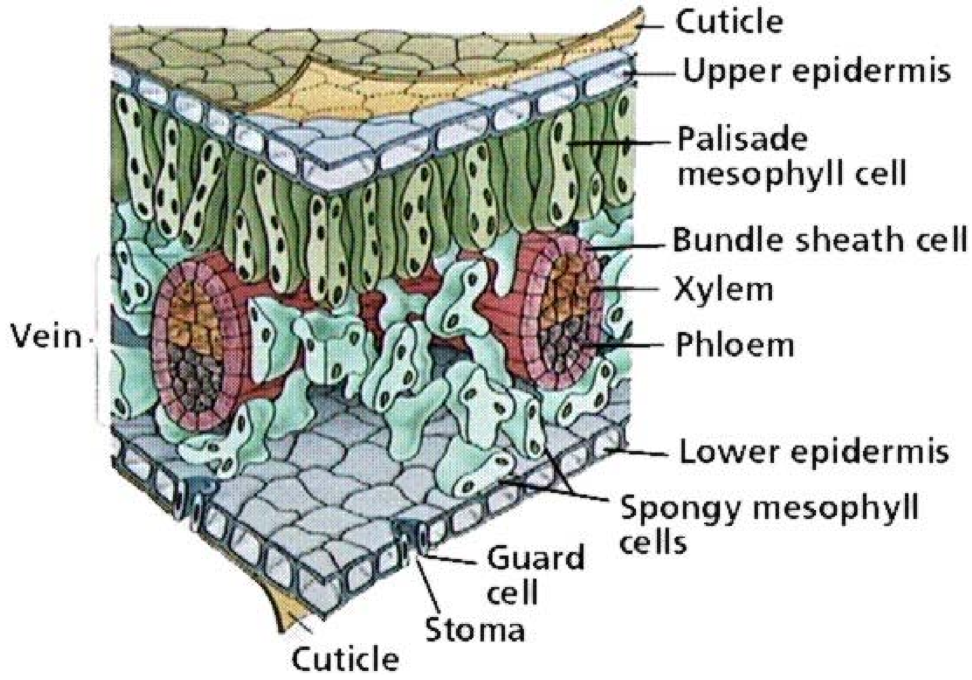


Figure 3.2: Leaf structure (source www.emc.maricopa.edu)

3.1.3 Human behaviour-related variables

Weather conditions and vegetation status are broadly involved in fire ignition and propagation. Nevertheless, especially on Europe most of fires causes are directly linked to human behaviours (see Cap. 1.3.6).

The presence of settlements, agricultural burning, pyromaniacs, barbecues and cigarettes contribute to increase the risk of accidental fires. These variables present a long-term variation and could be treated as static. Thus, the availability of ancient data is strictly necessary to provide reliable information about the human-derived incidence on fires.

3.2 Forest fire risk indices

An index of risk permits to better manage and compare information than using the values of the contributing variables directly. The values of variables identified as indicators of risk are managed by mathematical expressions. Thus, the result of these expressions is considered in order to extract an index which quantifies the risk throughout a numerical scale. However, the fire risk classification assumed different meaning in different contexts; computing the risk at national level or local scales or using different data sources and methodologies leads to results that are not immediately inter-comparables.

In literature, the indices of forest fire risk are several. A possible approach to present and collect them is to consider the time-scale of variation of the variables they considers. In particular, fire risk indices have been classified into long-term and short-term (figure 3.3).

Long term indices are those considering variables varying relatively little in the short or medium term. These indices, also known as structural indices, consider variables as type of fuel, fire history, amount of population, topography of the territory, soil type and proximity of roads; which have a nearly constant variability. Consequently, these indices are not frequently computed; i.e. once at year or less. Nevertheless, they are important to provide preliminary information about the risk helpful to improve the preparedness for forest fire fighting.

Another class of indices is the short term indices; which refers to variables varying nearly continuously. These indices, also known as dynamic indices, consider vegetation and meteorological conditions as evapotranspiration, relative humidity, wind and air temperature and, differently to the previous, they need to be computed more frequently. Their aim is to estimate the evolution of the risk.

More complex indices are made by the combination of long-term, short-term and human-derived variables and are known with the name of integrated or advanced indices (San-Miguel-Ayanz et al. 2003).

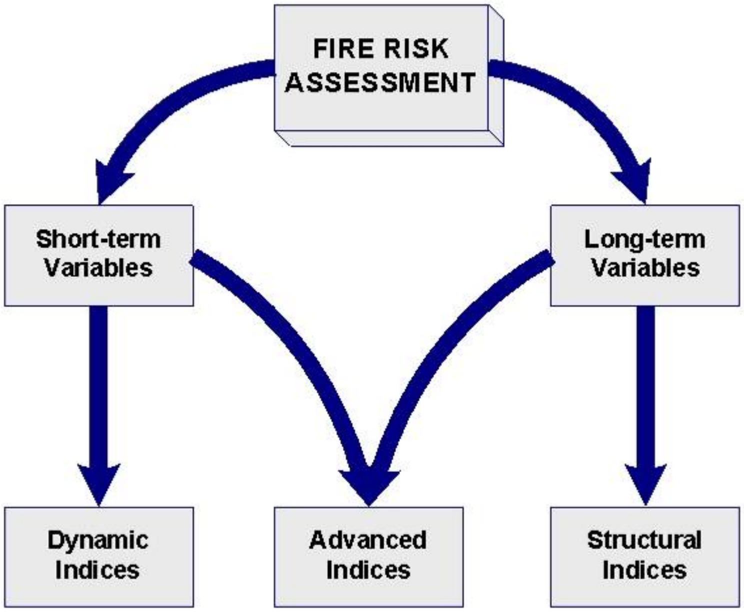


Figure 3.3: Forest fire risk indices classification

3.2.1 Meteo-derived indices

Since the weather conditions have been considered as the most significant component for fire ignition and propagation, several methods for the evaluation of fire danger based on meteorological data have been developed. The derived indices are referred as meteorological fire danger indices.

The most common indices used by forest fire and civil protection services in Europe are:

- The BEHAVE fine fuel moisture content (Viney 1991, Rothermel et al. 1994): related to the moisture content of fine dead fuel,
- The Canadian Fire Weather Index (FWI) (Van Wagner 1987): composed by six normalized indices indicating the daily variation of water content for fuels, the initial rate of spread for propagation, the quantity of fuel and the expected intensity of the flame front,
- The Portuguese index (Goncalves and Lourenco 1990): derived from Nesterov model and based on the assessment of atmospheric conditions in the proximity of the fuel layer,
- The Spanish ICONA method - probability of ignition (ICONA 1993): based on litter and fine dead fuels moisture content,
- The Sol-Drouet Numerical Risk (Drouet and Sol 1993): an ignition-propagation index,
- Italian Fire Danger Index (Palmieri et al. 1993): derived from Mc Arthur's model.

An extensive comparative study of various methods of fire danger evaluation based on meteorological parameters applied to southern European countries was presented by Viegas et al. (Viegas et al. 2000).

3.2.2 Vegetation indices derived by remote sensing

Vegetation structure and moisture condition also influence the ignition and propagation of forest fires. Vegetation stress has been evaluated and studied by quantifying the amount of water in the plants and relating it to water stress (Ceccato et al. 2001). For this purpose remote sensing has been frequently adopted to determine the level of vegetation stress (Cibula et al. 1992). The use of remote sensing permits to have information on large areas more quickly and easily than the use of meteorological data; which produces acceptable information only for places relatively close to the weather stations.

Vegetation indices are derived by remote sensing with the aim to attempt to evaluate the vegetation stress. They are formed from combinations of several spectral values indicating the amount or vigour of the observed vegetation. The simplest form of vegetation index is a ratio between measurements of reflectance in separate portions of the spectrum. The ratios have been defined by applying knowledge of the spectral behaviour of living vegetation as also explained in Cap.3.3.1. Ratios are effective in enhancing or revealing latent information when there is an inverse relationship between two spectral responses to the same biophysical phenomenon. If two features have the same spectral behaviour, ratios may provide additional information; but if they have quite different spectral responses, the ratio between the two values provides a single value that concisely expresses this difference. The ratio can be particularly effective for living vegetation because of the inverse relationship between vegetation brightness in the red and infrared regions. Many natural surfaces are about equally as bright in the red and near-infrared part of the spectrum with the notable exception of green vegetation. Red light is strongly absorbed by photosynthetic pigments found in green leaves, while near-infrared light either passes through or is reflected by live leaf tissues, regardless of their colour. Thus, areas of bare soil having little or no green plant material will appear similar in both the red and near-infrared wavelengths, while areas with green vegetation will be bright in the near-infrared and dark in the red part of the spectrum. That is, absorption of the red light by chlorophyll and strong reflection of infrared radiation by mesophyll tissue assures that the red and near infrared values will be quite different, and the ratio between infrared and red of actively growing plants will be high. Non vegetated surfaces, including open water, man-made features, bare soil and dead or stresses vegetation will not display this specific spectral response, and the ratios will be low in magnitude (Campbell 2002).

Indices based on the vegetation stress estimate are called vegetation indices. They mainly derived by the simple Vegetation Index (Tucker 1979), $\mathrm{VI} = \rho_{\mathrm{NIR}} - \rho_{\mathrm{red}}$, and by the Ratio Vegetation Index (Jordan 1969), RVI= $\rho_{\mathrm{NIR}} / \rho_{\mathrm{red}}$.

A list of the most common indices of vegetation includes:

- The Normalized Difference Vegetation Index (NDVI):

$$\mathrm{NDVI} = \frac{\rho_{\mathrm{NIR}} - \rho_{\mathrm{red}}}{\rho_{\mathrm{NIR}} + \rho_{\mathrm{red}}}$$

The NDVI is the most commonly used index for forest fire risk assessment in which the difference in reflectance is divided by the sum. This compensates for changing illumination conditions, surface slope, aspect, and other extraneous factors and produces a number between -1 and +1. The typical range of actual values is about 0.1 for bare soils to 0.9 for dense vegetation. NDVI is thought to be more sensitive to low levels of vegetative cover (Rouse et al. 1974).

- The Soil-Adjusted Vegetation Index (SAVI):

$$\mathrm{SAVI} = \frac{\rho_{\mathrm{NIR}} - \rho_{\mathrm{red}}}{\rho_{\mathrm{NIR}} + \rho_{\mathrm{red}} + \mathrm{L}} * (1 + \mathrm{L})$$

This index resembles the NDVI with some added terms to adjust for different brightness of background soil. In principle, the term L can vary from 0 to 1 depending on the amount of visible soil. The constant L is empirically determined to minimize the index sensitivity to soil background reflectance variation. However, 0.5 works as a reasonable approximation for L when the amount of soil in the scene is unknown and for intermediate vegetation cover ranges. The factor (1+L) set the range of SAVI values between -1 and +1, as the range of the NDVI (Huete 1988).

- Normalized Difference Water Index:

$$\mathrm{NDWI} = \frac{\rho_{\mathrm{NIR}} - \rho_{\mathrm{SWIR}}}{\rho_{\mathrm{NIR}} + \rho_{\mathrm{SWIR}}}$$

This index was proposed for remote sensing of vegetation liquid water from space as a complementary index for NDVI. The formula Is equivalent to NDVI with the visible channel replaced by a short wave infrared reflectance at 1.24 µm (Gao 1996).

- Relative Greenness Index:

$$\mathrm{RGI} = \frac{\mathrm{NDVI}_{\mathrm{i}} - \mathrm{NDVI}_{\mathrm{min}}}{\mathrm{NDVI}_{\mathrm{max}} - \mathrm{NDVI}_{\mathrm{min}}} * 100$$

It is defined as the relative variation of NDVI, with respect to its maximum and minimum of a long period. In this way, the change due to the climatic conditions can be better discriminated, since the absolute value of the NDVI is sometimes more related to the landscape composition instead of seasonal dynamism (Goward et al. 1991).

Several other vegetation indices have been introduced during last years in order to improve the previously or to obtain different results (Ceccato et al. 2002, Ceccato et al. 2002). Nevertheless, although such ratios have been shown to be powerful tools for studying vegetation, they must be used with care. Value of vegetation indices can be influenced by many factors, as viewing angle, soil background and differences in row direction and spacing in the case of agricultural crop, different calibration of the sensors or leaf orientation.

3.2.3 Long-term and Advanced indices

Long term fire risk indices are those based on parameters that do not present high variation in a short period of time. These indices are indicators of stable conditions that, anyhow, could influence fire occurrences. They are frequently used to determine areas having an intrinsic high level of fire risk. The Fire Probability Index and the Vulnerability Index are examples of indices belonging to this category (San-Miguel-Ayanz 2002). The Fire Probability Index is related to the probability of fire occurrence and evaluates the probability of ignition. It includes the estimation of the fuel available for burning, the topography of the territory and socio-economical variables, human factors. The Vulnerability Index, or Likely Damage Index, evaluates the level of possible damages in relation to the considered area. It estimates the damage that a fire would cause in a case it happens in a particular area. Natural areas of particular environmental interest, areas subjected to soil erosion and areas close to human settlements are an example of critical areas.

Indices considering variables coming independently from the long-term and the short-term group are called advanced indices. An example are the National Fire Danger Rating System, NFDRS (Deeming and Burgan 1977) and the Fire Potential Index, FPI (Burgan et al. 1998, Lopez et al. 2002). The NFDRS evaluates the risk of fire by means of weather conditions and estimates of moisture content. It allows the possibility to discriminate between 20 different fuel models. The FPI is based on the knowledge of three vegetation variables; the live ratio, the moisture content and the fuel type. The live ratio refers to the percentage of live fuel load with respect to the total fuel load. The moisture content refers to small dead fuels and fuels cured during the dry season. The fuel type classification is used to assign dead fuel extinction moisture content values.

4 Remote Sensing applications

Remote sensing is the science and the art of obtaining information, measurement or acquisition, through the analysis of data acquired without a direct contact with the object, area, or phenomenon under investigation (Lillesand and Kiefer 1987).

The introduction of remote sensing in forestry gave the advantage to collect information on large areas quickly and easily. In general, remote sensing includes activities as recording, processing, analysing, interpreting, and obtaining useful information from the data generated by remote sensing systems. Figure 4.1 illustrates schematically the generalised activities and elements involved in a remote sensing process. The energy emitted naturally or artificially is reflected by the atmosphere and by the vegetation. The reflected energy is detected and electronically transmitted back to the receiver station. This information is subsequently processed, analysed and interpreted depending on the situation (Clevers 2003).

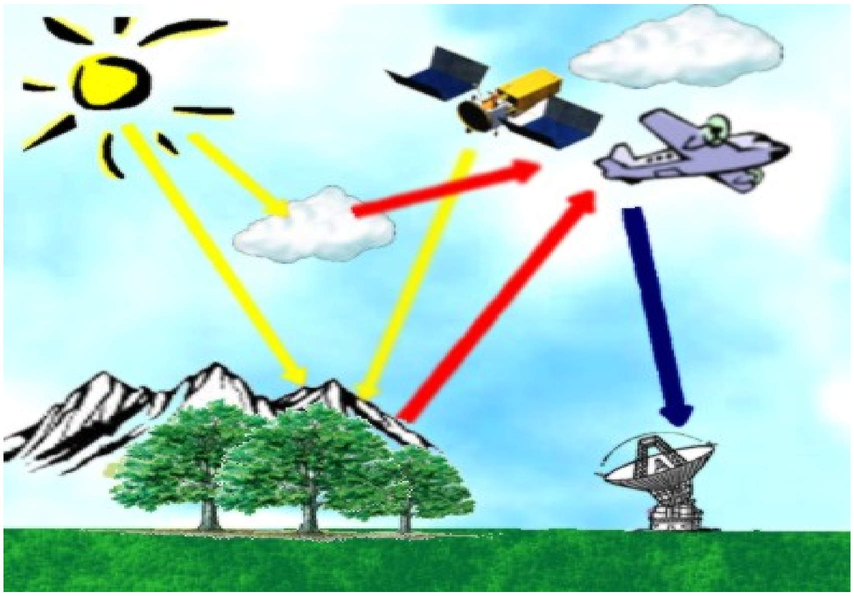


Figure 4.1: Simple scheme of a remote sensing process.

4.1 Electromagnetic Radiation

A first requirement for remote sensing is to have an energy source to illuminate the target, i.e. the vegetation. The energy incidents the target, E_I, is reflected, E_R, absorbed, E_A, and transmitted, E_T, following the equation $E_I=E_R+E_A+E_T$. This represents just a simplified equation since each target presents a different percentage of reflected, absorbed and transmitted energy and energy interactions with other objects are not considered (figure 4.2).

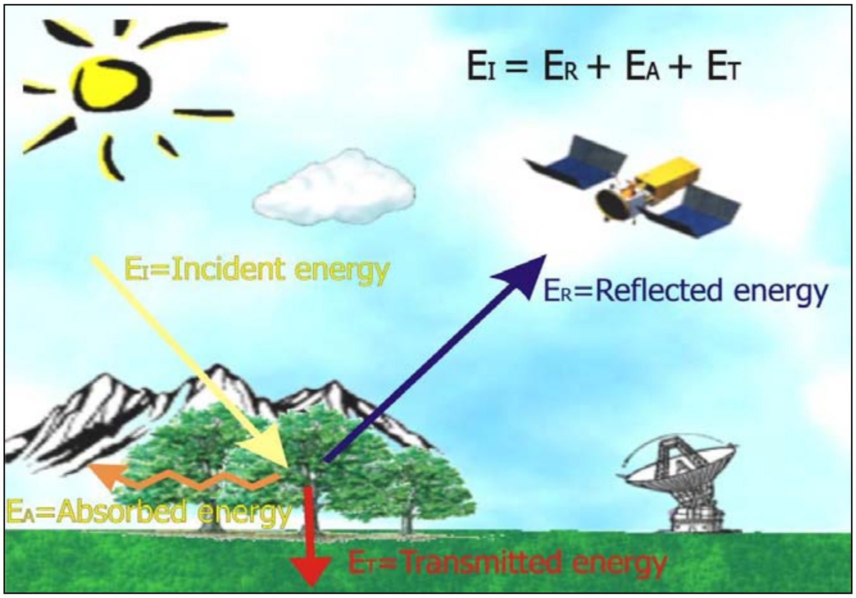


Figure 4.2: Energy interactions

The energy is in form of electromagnetic radiation and follows the wave theory (figure 4.3). It travels assuming a sinusoidal path in which the wavelength, λ, is represented by the distance between two consecutive waves and the frequency, υ, is represented by the number of crests passing at a fixed pointing in a given period of time. According to the wave theory, wavelength and frequency are in relationship by the formula λ = *c* / υ; where *c* is the light speed having the constant value of 299.893 kilometres per second.

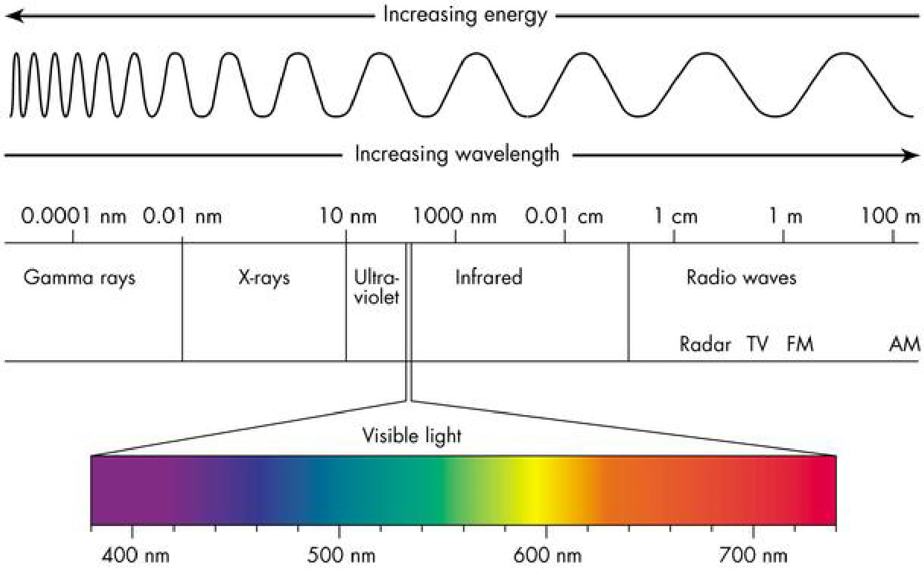


Figure 4.3: Electromagnetic Spectrum (source www.mhhe.com)

4.2 Atmospheric interactions

The atmosphere consists mainly of molecular nitrogen and oxygen with in addition water vapour and particles as dust, soot, waster droplets and ice crystals. The radiation used for remote sensing travels through the atmosphere and, consequently, these elements influenced it. The most important processes of interaction are scattering and absorption. Scattering phenomenon occurs when particles of large molecules of atmospheric gas or particles suspended in the atmosphere interact with and cause the electromagnetic radiation to be redirect from its original path. The effect of scattering is to redirect radiation so that a portion of the incoming solar beam is directed back toward space, as well as toward the earth's surface. On the other hand, absorption phenomenon occurs when the atmosphere prevents, or strongly attenuates, transmission of radiation through the atmosphere. The most efficient absorbers of solar radiation are water vapour, carbon dioxide and ozone.

Moreover, the earth's atmosphere is not completely transparent to electromagnetic radiation because the gases it contains form a sort of barrier to the transmission of electromagnetic radiation. Only energy of certain wavelength is selectively transmitted. Wavelengths relatively easily transmitted through the atmosphere are those belonging to atmospheric windows; regions of the electromagnetic spectrum in which transmittance is more than 90% (figure). Positions, extents, and effectiveness of atmospheric windows are determined by the absorption spectra of atmospheric gases. Atmospheric windows are of obvious significance for remote sensing, since they define the wavelengths that can be better used. Energy of wavelength not inside the windows is severely attenuated by the atmosphere and therefore cannot be effective for remote sensing (Campbell 2002).

4.3 Spectral reflectance

Many remote sensing systems operate in the wavelength regions in which reflected energy predominates. The reflected energy is detected, measured and translated into information about the observed object. The ratio of incident energy on a target to reflected energy from the object is referred to as reflectance, having range between 0 and 1, and the equipments to measure it are called spectrometers. The reflectance using as incident light source the solar light is called Albedo.

Reflectance with respect to wavelength is called spectral reflectance and the graph of the spectral reflectance as a function of wave length is the spectral reflectance curve. A basic assumption in remote sensing is that spectral reflectance is unique and different from object to object. Experience has shown that many earth surface features of interest can be identified, mapped and studied on the basis of their spectral characteristics (figure 4.4).

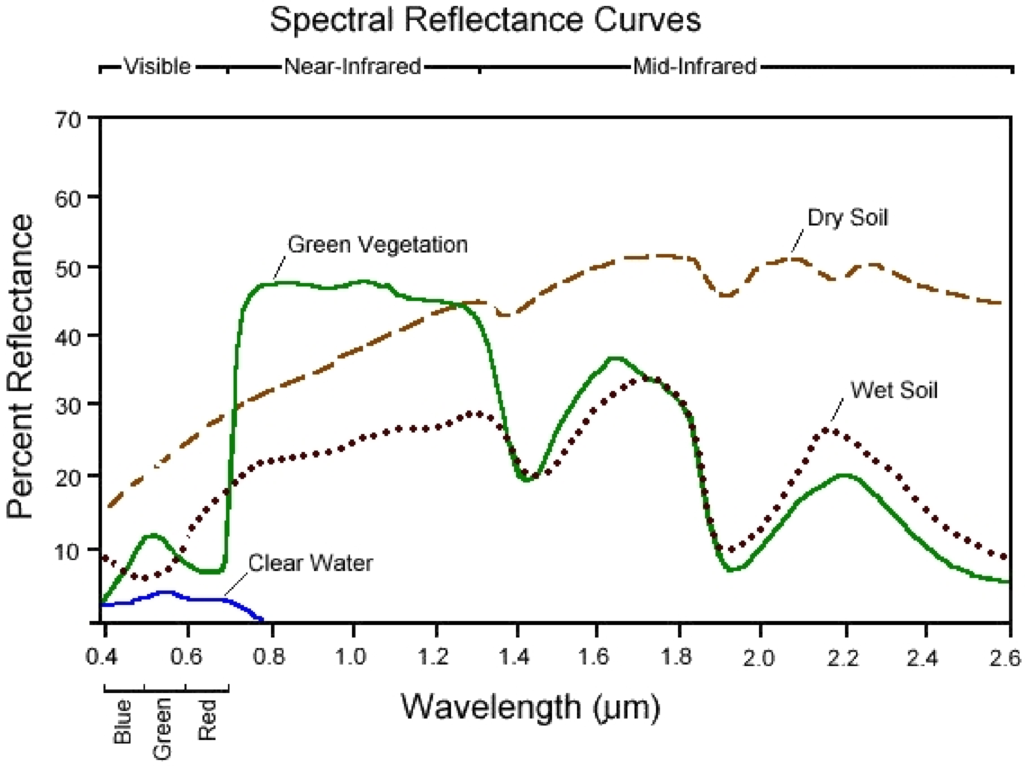


Figure 4.4: Typical spectral reflectance curves for green vegetation, dry soil, wet soil and water.

4.3.1 Spectral behaviour of living leaves

Knowledge of how solar radiation interacts with vegetation is required to interpret and process remote sensing data of natural resources. The chlorophyll molecules potentially absorb blue and red light for use in photosynthesis. If less of the green light was absorbed, more would be reflected. Thus, a human observer, who sees only the visible spectrum, sees the dominant reflection of green light as the colour of living vegetation. In the near infrared spectrum reflection of the leaf is controlled by the structure of the spongy mesophyll tissue and not by plant pigments. The cuticle and epidermis are almost completely transparent to infrared radiation, so very little infrared radiation is reflected from the external portion of leaves. At the edge of the visible spectrum, as the absorption of red light by chlorophyll pigments begins to decline, reflectance rises sharply. Thus, if reflectance is considered not only in the visible but across the visible and the near infrared, peak reflectance of living vegetation is not in the green but in the near infrared (figure 4.5). This behaviour explains the great utility of the near infrared spectrum for vegetation studies, and facilitates separation of vegetated from non vegetated surfaces, which result much darker in the near infrared (Danson et al. 1992). Furthermore, differences in the reflectivity of plant species often are more pronounced in the near infrared than they are in the visible, meaning that discrimination of vegetation classes is something made possible by using near infrared reflectance. Moreover, as a plant matures or is subjected to stress by disease, insect attack, or moisture shortage, the spectral characteristics of the leaf may change. In general, these changes apparently occur more or less simultaneously in both the visible and near infrared regions, but changes in near infrared reflectance are often more noticeable (Knipling 1970, Elvidge 1990).

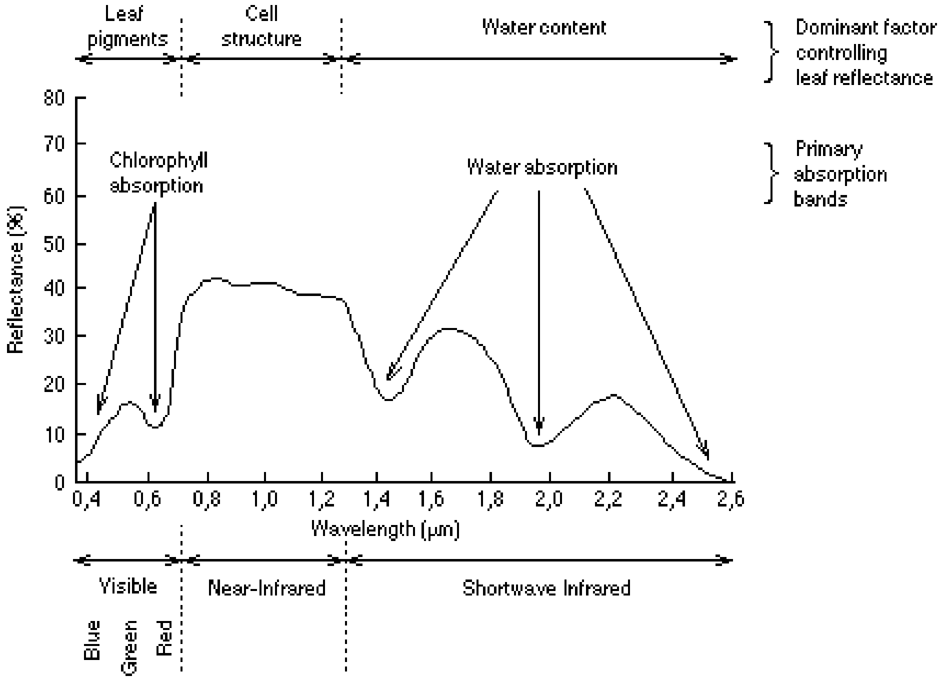


Figure 4.5: Factors controlling leaf reflectance

4.4 Sensors

Sensor is the particular instrument able to measured electromagnetic radiation. It is classified as active or passive by considering the energy it detects. An active sensor presents a built-in source of radiation. The sensor emits energy toward the target to investigate and detects and measures the reflected energy. The observed target plays a passive role. A passive sensor collects the energy reflected from a target with no active pulse of energy from the sensor. It is sensitive to energy that is naturally available. Thus, energy can be detected as long as the amount of energy is large enough to be recorded.

A single sensor could be not sensitive to all the wavelengths. Each sensor is characterised by spatial resolution, spectral resolution, radiometric resolution and temporal resolution. Depending on the application, the quality of the information retrieval can be improved by selecting optimum spectral bands or band combinations.

The details discernible in an image are dependent on the spatial resolution of the sensor. The spatial resolution describes the smallest spatial separation of two measurements which the sensor is able to resolve. It defines the size of the smallest unit of information in an image, the pixel size. Depending on the sensor and the satellite's orbit, the spatial resolution may vary from less than one meter to several kilometres.

The spectral resolution describes the number and width of channels that a sensor samples within the electromagnetic spectrum. The finer the spectral resolution, the narrower the wavelengths range for a particular channel or band. A very high spectral resolution facilitates fine discrimination between different targets based on their spectral response in each of the narrow bands.

The radiometric resolution corresponds to the capabilities to detect energy differences in terms of power. The finer the radiometric resolution of a sensor the more sensitive to detect small differences in reflected or emitted energy. Image data are usually displayed in a range of grey tone. The radiometric resolution refers to the number of grey values available in image product.

The temporal resolution is linked to the concept of revisit period, which refers to the time a satellite needs to complete one entire orbit cycle (Hoffmann 2000).

4.5 Satellites

The sensors are situated in vehicles called platforms. The platforms can be located within the Earth atmosphere, directly on the ground, on an aircraft or on a balloon, or outside the atmosphere, on a spacecraft or on an artificial satellite.

Satellites provide a great deal of remote sensing imagery commonly used today, although ground based and aircraft platforms are continually used. Nevertheless, satellites have several unique characteristics which make them particularly useful for the remote sensing of the Earth's surface. A satellite with remote sensors to observe the Earth is called a remote sensing satellite or Earth observation satellite.

A satellite follows a path called orbit that match to the capabilities and objectives of the sensor carried. Orbit selection can vary in terms of altitude, orientation and rotation. Very high altitude satellites, which are able to observe the same portion of Earth's surface at all times have orbits called geostationary. The altitude is about 36.000 kilometres and the speed matches the one of rotation of the Earth; hence, they seem to be stationary. Weather and communication satellites follow this kind of orbit.

Satellites mainly for land area observation and vegetation monitoring, instead, follow a polar orbit. They have an altitude of several hundred kilometres and many of them are sun-synchronous. They follow an orbit, typically from north to south, which, in conjunction to the Earth's rotation allows them to cover most of the Earth's surface within a certain period of time.

4.6 Remote Sensing products

The energy recorded by a sensor is successfully transmitted, often in electronic form, to a receiving station where the data is processed. Generally, some pre-processing operation is performed at this level to correct sensor and platform radiometric and geometric distortions of data, consequence of variations in scene illumination and viewing geometry, atmospheric conditions, sensor noise and response.

Concluding, platforms, sensors and data products are several. Each of these presents different characteristics that make it suitable more for some applications than for others, depending on the specific needs. The data price is also variable and is related to the resolution, the quality and the availability of the required information. Different products have to be supposed as complementary and not competitive.

4.7 NOAA series

The term NOAA stands for National Oceanic & Atmospheric Administration and represents an agency of the United States Department of Commerce. It operates a network of weather satellites, the National Weather Service, the National Hurricane Center and cooperates with the national Ice Center (http://www.noaa.gov/). A series of polar orbiting environmental satellite operates by the US NOAA is the NOAA-POES, Polar Orbiting Operational Environmental Satellite (figure 4.6). They have a mean orbital period of 102 minutes at an altitude of about 850 Km, a repeated cycle of approximately nine days and are sun synchronous (figure 4.7). The low spatial resolution they present allow studies at continental scale. Studies that could be disadvantaged by the low revisit capabilities or relatively small fields of view of other satellites as Landsat or SPOT.

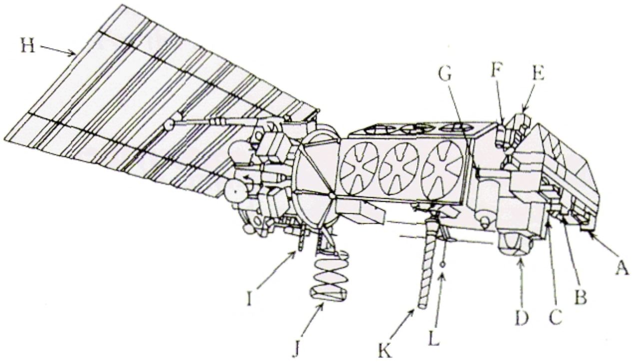
The first of the current generation of NOAA satellites was the prototype TIROS-N, launched in October 1978. At the moment, only NOAA-16 and NOAA-17 satellites are fully operating. The NOAA-15 is still available but only as a backup instrument. These last three satellites are also known as NOAA-K (15), NOAA-L (16) and NOAA-M (17) (U.S. Department of Commerce 1998, 2000).

The main instrument carried on the NOAA satellites is the Advanced Very High Resolution Radiometer, AVHRR; where Very High Resolution refers to the ten-bit radiometric resolution and not to spatial or spectral resolution. This instrument, first developed for the observation of clouds, land and sea surface, presents a spatial resolution of 1 Km in the visible and infrared wavelength region and its large swath width, about 2700 Km, permits daily coverage of the same site at different look angles. The earlier AVHRR instruments on NOAA 9, 10, 11, 12 had 5 bands in the visible (band 1), NIR (band 2), MIR (band 3) and Thermal IR (band 4, 5) regions. Band 1 (0.58-0.68 µm) and band 2 (0.725-1.10µm) were designed to measure reflected energy, band 4 and 5 (10.5-11.3µm and 11.5-12.5µm) to measure emitted energy and band 3 (3.55-3.93µm) to measure energy that is a mixture of reflected and emitted energy. The newer AVHRR instrument starting from the NOAA-15 includes a new band in the SWIR. This band shares the same transmission channel with the MIR band which is designated band 3A, while the SWIR band is band 3B. Only one of the 3A or 3B bands could be activated at any instant.

AVHRR data are acquired in High Resolution Picture Transmission, HRPT, Local Area Coverage, LAC, and Global Area Coverage, GAC, format. The HRPT format provides full resolution images transmitted to a local ground station as they are being collected. The LAC format provides full resolution images recorded with an on-board tape recorder for subsequent transmission during a station overpass. The GAC format provides daily subsampled, to about 4 Km pixel separation at nadir, global coverage images recorded on-board on a tape recorder and transmitted to a ground station afterwards.

Even though the NOAA series was designed primarily for meteorological applications, the AVHRR instrument has shown applicability in a variety of environmental linked earth observation application, such as:

- Hydrological applications (Snow extension cartography, extension of flood waters);
- Resources (NDVI, fire detection);
- Ground use (Urban effects);
- Geological applications (Tectonic and lithologic cartography);
- Natural hazards (Volcanoes, Earthquakes, Floods, Fires);
- Marine applications (SST, Water quality, Oil spills);
- Climatic Applications (Storms, Cloudiness, Winds).



A : AVHRR sensor, B : the stratospheric sounding unit, C : high resolution infrared radiation sounder, D : microwave sounding unit (B - D : TOVS), E : observation unit for proton and electron, F : α–particle measure unit, G : earth sensor, H : solar battery array, I : S band antenna, J : VHF antenna, K : data collection system antenna, L : X band antenna

Figure 4.6: NOAA satellite appearance

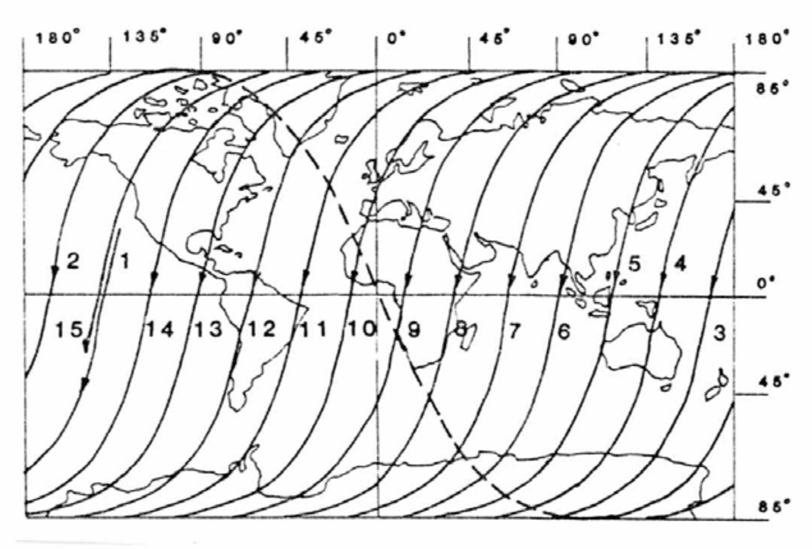


Figure 4.7: NOAA orbits

5 Data and Methods

5.1 Study area

The Spanish territory is located in the south-western part of Europe. It presents an extension of 505960 Km^2 that is divided into 50 provinces, grouped into 17 autonomous communities and 2 autonomous cities (figure 5.1).

Figure 5.1: Territory of Spain

The Spain's territory is prevalently occupied by high plateaus and mountain ranges such as the Pyrenees or the Sierra Nevada and its wide extension leads to different climatic areas. A Northern Atlantic coastal area characterised by prevalently winter precipitations and mild summers. An inner area characterised by very cold winters and hot summers, and the Canary Islands area characterised by a subtropical weather, with mild temperature all over the year. Nevertheless, the wider area is represented by the Mediterranean region. That is a mostly temperate area situated in the eastern and southern part of Spain with a rainy period concentrated during spring and autumn. It is characterised by a high thermal and pluvial variability across seasons and by an evident lack of rainfall during summer. These characteristics affect the forest territory and are directly responsible of factors as erosion, desertification and forest fires.

Forest covers almost 29% of the total land area corresponding to about 14.4 millions hectares, which sets Spain as the fourth European country in terms of forest resources. The most productive forests are found in the Atlantic coastal zone and are composed mostly of pines (*Pinus pinaster* and *P. radiata*) and eucalyptus (*Eucalyptus globulus*), although some mixed natural forests of oak (*Quercus robur* and *Q. patraea*) and beech (*Fagus sylvatica*) are also present. In the Pyrenees, there are forests of silver fir (*Abies alba*), beech and pine, depending on altitude. The remainder of the country, where Mediterranean conditions predominate, is notable for its wealth of biological diversity. In some places *Quercus spp.* are found in pure stands, constituting wooded meadows (an agrosilvopastoral combination typical of Mediterranean zones) or mixed with pines and a wide variety of shrubs and scrub vegetation. In mountainous Mediterranean regions *Pinus spp.* become increasingly frequent as the altitude increases.

In this ecosystem, forest fires represent a major problem. Although with large variations from year to year, on average about 190519 ha are burned each year starting from 1980, with a figure over 400000 ha in 1985, 1989 and 1994. The improvement in methods of fire extinction and fire management helped to steadily decrease the average burnt area over the years even thought the human behaviour lead to a steady increase of the number of fires (figure 5.2).

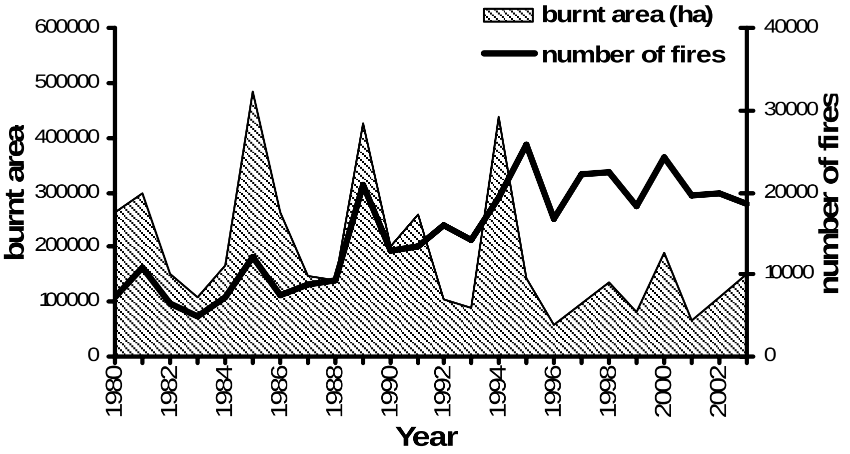


Figure 5.2: Burnt area and number of fires in Spain during the last 23 years.

Comparing to the whole European Mediterranean region, Spain represents the country most subject to the problem of forest fire with a percentage of burnt area during last 23 years equal to the 38% of the entire Mediterranean region total burnt area (European Commission 2004). Similar result is obtainable by summing up the entire burnt area of Italy, France and Greece together (figure 5.3). Only Portugal was subjected to a number of forest fires bigger than Spain, even though the order of magnitude is similar (figure 5.4).

Every year, on average, Spain is subject to 14965 forest fires, producing 190519 hectares of burnt area and 298 million euros of consequent economical loss. During year 2003, the 34% of the total number of fires in the European Mediterranean region took place in Spain producing 149000 hectares of burnt wooded area and an estimated consequent economical loss of 405570000 euros, primary product plus environmental benefit (Ministerio de Medio Ambiente 2004).

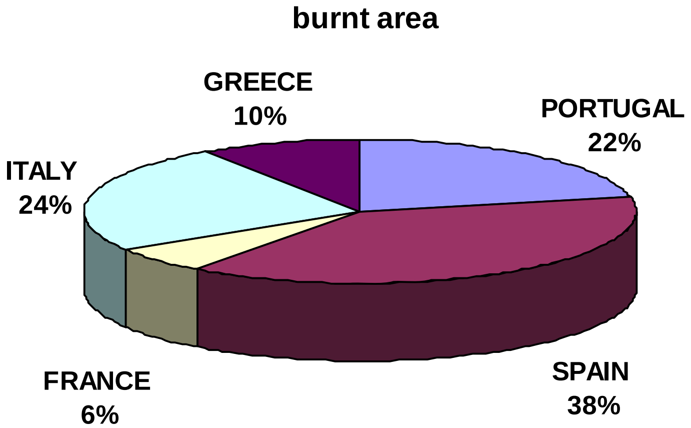


Figure 5.3: Percentage of the total burnt area in the EU Mediterranean region during the last 23 years.

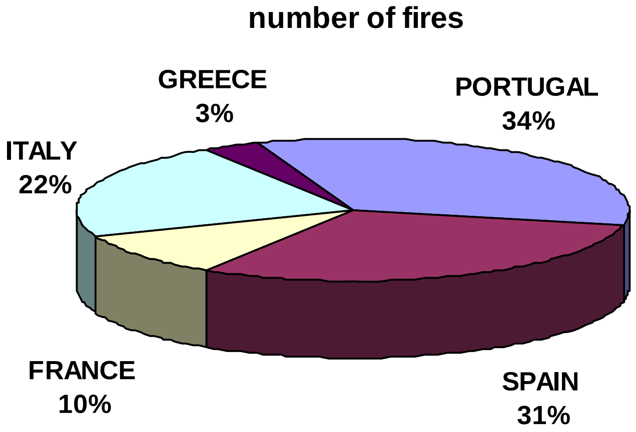


Figure 5.4: Percentage of the total number of fires in the EU Mediterranean region during the last 23 years.

5.2 Ground Data

A process of validation of an index of forest fire risk requires a harmonised dataset of images indicating levels of risk and a consistent dataset of fire occurrences. This dataset of information is necessary in order to assess the potential of the analysed index. It should collect all the information useful in order to locate fire events both temporally and spatially. Moreover, the possibility to dispose of a huge dataset of events makes the process of validation more reliable. In this chapter the European Database of fire events, known as Common Core Database, is introduced and a description of the adopted dataset of events is presented. The fire event information was extracted from the European Forest Fire Information System, EFFIS, which contains information on single fire events collected in the frame of the European Regulation EC 2152/2003 concerning monitoring of forests and environment interactions in the Community (European Commission 2003).

5.2.1 Common Core Database

In 1990, through the Standing Forestry Committee's Working Group on forest fires, the Member States decided starting exchanging information regarding forest fires (European Commission 1996). The impact produced by this exchange led to the introduction, on 11 April 1994, of the Regulation EC No 804/94 (European Commission 1994) to establish rules for the application of a forest fire information system as reported on Council Regulation EEC No 2158/92 (European Economic Community 1992). The regulation asked each Member State to collect a harmonized set of information on forest fires occurred yearly. This set had to contain at least a number of fixed items referred as the minimum common core of information on forest fires, permitting a comparison at Community level. For each officially recorded forest fire, the requested details were reported by table 5.1.

The resulting system of information, as referred as Common Core Database, aimed to promote exchanges of information on forest fires, to evaluate the impact of measures taken by Member States and the Commission to protect against fire, to evaluate periods, degrees and causes of risk and to develop strategies for protection with emphasis on the elimination and reduction of causes. At the beginning, the system was covering 224 administrative areas in the South of Europe. The definition of administrative commune level adopted was the one defined by Gisco (Eurostat 2004) Nevertheless, the system has steadily increased and, at the present, it regroups 319 administrative areas in Germany, Portugal, Spain, France, Italy and Greece. The evolution of the considered territory is presented in figure 5.5.

Table 5.1: Items required for a registered forest fire

FIELD NAME	DESCRIPTION
Date of first alert	the local date (day, month and year) on which the official forest fire protection services were informed of the outbreak of the fire
Time of first alert	the local time (hour and minute) at which the official forest fire protection services were informed of the outbreak of the fire
Date of first intervention	the local date (day, month and year) on which the first fire-fighting units arrived on the scene of the forest fire
Time of first intervention	the local time (hour and minute) at which the first fire-fighting units arrived on the scene of the forest fire
Date on which the fire was extinguished	the local date (day, month and year) on which the fire was completely extinguished
Time at which the fire was extinguished	the local time (hour and minute) at which the last fire-fighting units left the scene of the forest fire
Location of outbreak	the name of the commune and the successive territorial units to which it belongs (province or department, region, State) in which the outbreak of the fire
Total area burnt	the total area covered by the fire and the unit of area used. The unit of area and the precision of the measurement should be those customarily used in the Member State
Breakdown of burnt area into wooded and unwooded land	the wooded area and the unwooded area covered by the fire and the unit of area used or the respective percentages of the total area covered by the fire on wooded and unwooded land. The unit of area and the precision of the measurement should be those customarily used in the Member State
Presumed cause of the forest fire	the presumed cause of the fire according to the following four categories: 1. cause of fires unknown; 2. natural cause, e.g. lightning; 3. accidental cause or negligence, e.g. accidents caused by power lines, railways, works, barbecues, a bonfire that got out of control; 4. fires started deliberately, i.e. by someone intending to destroy an area of forest for whatever motive
Commune code	the European code for the commune in which the fire broke out. This code consists of nine digits, representing the code of the Member State, the region, the province and the commune. By means of the code the location of the fire for administrative purposes can be established at once

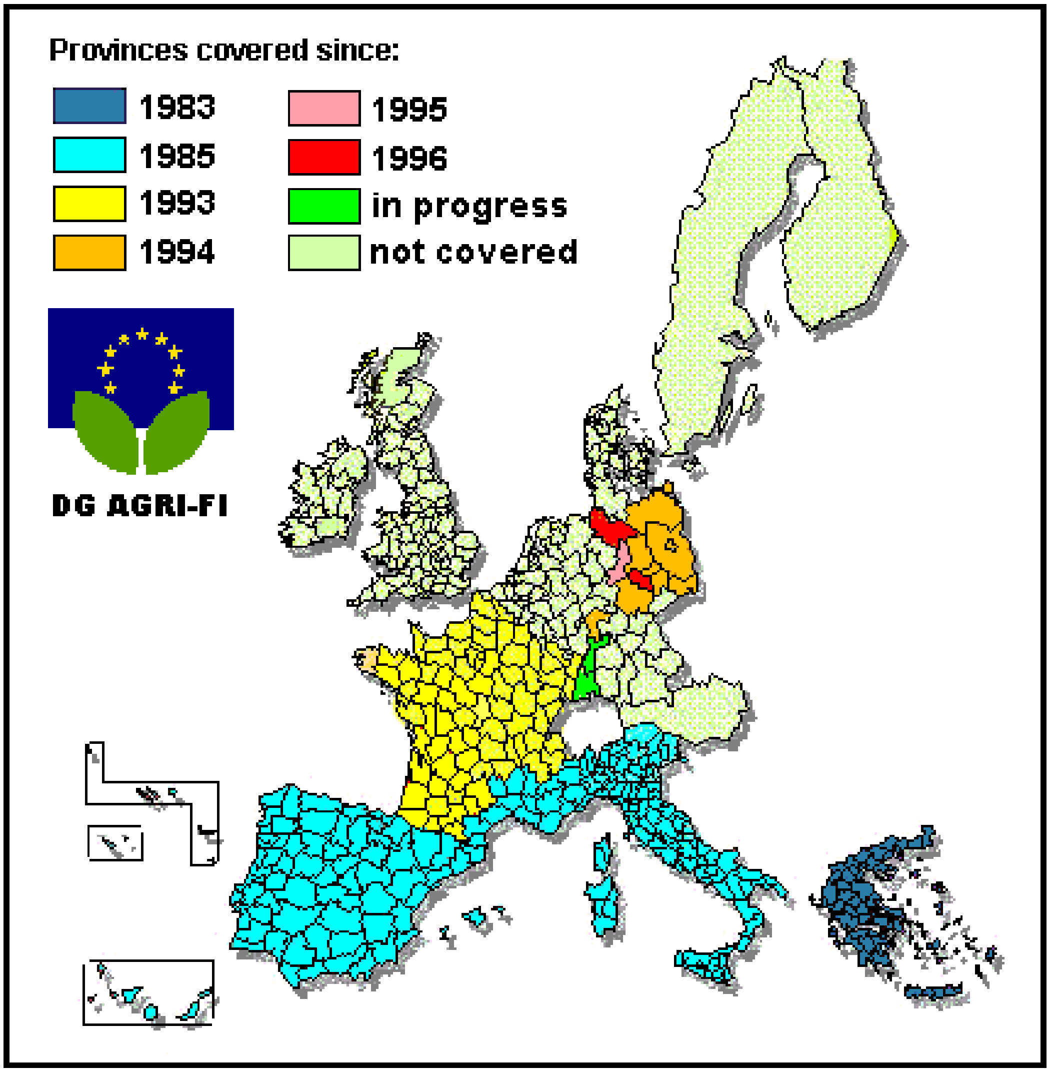


Figure 5.5: Geographic coverage of the Common Core adherent provinces (source DG AGRI-FI).

The Forest Focus Regulation (EC) No 2152/2003 (European Commission 2003) concerning monitoring of forests and environment interactions in the Community substituted Regulation EC No 2158/92 after its expiration. Since 1999, a research group has been set up, at the European Commission DG Joint Research Centre, to work specifically on the development of a European Forest Fire Information System, EFFIS, as requested by Regulation. The previous Common Core Database still continues to be part of the European Fire Database included in EFFIS.

5.2.2 Available database

As explained in the previous chapter, information regarding forest fire was collected at Member State level; which implies that the available database was made by a collection of data coming from different sources. A check of data consistency was necessary in order to assess the reliability of the information. The data consistency was verified controlling the information stored in each record of the database. It was concluded that Italy, France and Spain presented the most reliable information regarding fire data. Nevertheless, a further control highlighted a persistent mistake in the filling of the local code fields. This commune code, essential to locate spatially the fire outbreak, was often missed and not always immediately available. The impossibility to locate the fire made the information available useful only for general statistical analysis. In particular, only after the year of 1998, it was possible to identify spatially any fire event. Thus, in order to remedy this inconvenient, appropriate procedures of data recovering were studied and applied to the database entries by using PL/SQL. With these procedures we analysed the records of the database trying to re-establish, when possible, the right location code (local code) for a fire. This permitted to increase, sometimes significantly, the percentage of allocable events. Table 5.2 shows the percentage of fire events contained in the database that were possible to allocate spatially before and after the recovery procedure adopted. The obtained improvements are immediately noticeable.

Table 5.2 Percentage of exact local codes before and after the procedure of recovery adopted.

%	ITALY		FRANCE		SPAIN	
	before	**after**	**before**	**after**	**before**	**after**
1985	86.60%	99.97%	99.11%	98.87%	99.48%	99.48%
1986	84.82%	99.98%	99.89%	99.89%	99.49%	99.49%
1987	83.56%	100.00%	97.21%	97.21%	99.49%	99.50%
1988	85.68%	99.95%	99.91%	99.91%	99.51%	99.53%
1989	81.83%	99.99%	99.82%	99.82%	99.07%	99.27%
1990	82.24%	99.96%	99.73%	99.73%	99.02%	99.05%
1991	86.54%	99.92%	99.75%	99.75%	99.12%	99.12%
1992	87.36%	99.90%	99.93%	99.93%	98.87%	98.87%
1993	84.82%	99.68%	99.47%	99.47%	98.69%	98.69%
1994	83.93%	99.85%	99.83%	99.83%	99.14%	99.14%
1995	82.78%	99.81%	99.31%	99.31%	99.24%	99.24%
1996	91.19%	99.61%	99.92%	99.92%	99.27%	99.27%
1997	86.77%	86.77%	82.04%	99.86%	99.28%	99.70%
1998	0.00%	0.00%	0.00%	99.98%	0.00%	97.95%
1999	0.00%	0.00%	0.00%	99.96%	0.00%	97.60%
2000	0.00%	0.00%	0.00%	99.93%	0.00%	0.00%

5.2.3 Study database

After the database adjustments, a huge amount of data was available for the entire Europe and in particular for Spain; which presented a good percentage of reconstructed local codes. Nevertheless, it was decided to decrease the size of the handled information retaining only fires having a total burnt area bigger than 50 hectares. A direct comparison between the total area burned by all the fires and the area burned only by fires bigger than 50 hectares highlighted how these are responsible of most of the damages in Europe. Table 5.3 reports the example for year 2001.

Table 5.3: Breakdown of number of fires and area burnt (ha) by size of fire in 2001 (source DG AGRI-FI)**.**

		Total	**>50 ha**	**Percentage**
SPAIN	**No**	19097	296	2%
	Area(ha)	92384	55618	60%
FRANCE	**No**	4256	68	2%
	Area(ha)	20466	14770	72%
ITALY	**No**	7237	0	0%
	Area(ha)	81500	0	0%
PORTUGAL	**No**	26900	332	1%
	Area(ha)	111832	81383	73%
GERMANY	**No**	380	0	0%
	Area(ha)	87	0	0%
TOTAL	**No**	58169	711	1%
	Area(ha)	311098	156209	50%

Besides, the retained period of study was reduced to the period between 1st of May and 31st of October. These months corresponding to the so called fire campaign period, in countries having prevention scheme and forest fire means in place. In the Mediterranean Region this period is also characterised by small amounts of precipitation and corresponds to yearly peak in the number of fires (European Commission 2003). Figure 5.6 reports the monthly distribution of fire events and burnt area in 2001 for Germany, Spain, France, Italy, Portugal and Cyprus (European Commission 2003).

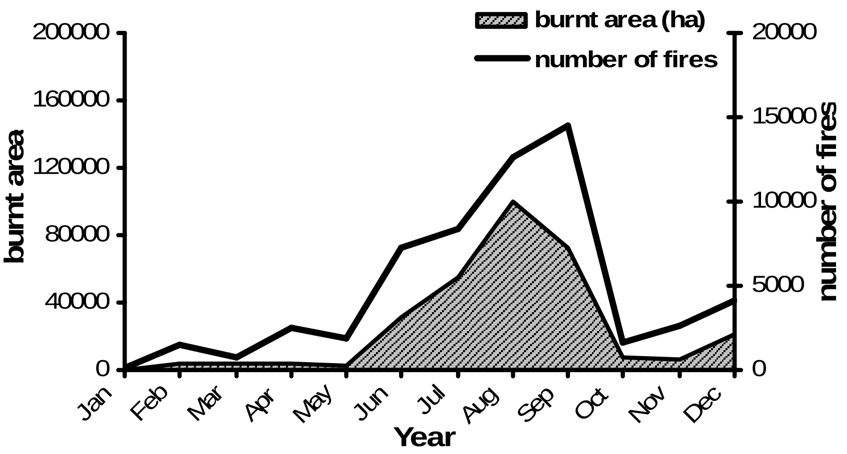


Figure 5.6: Monthly distribution of number of fires and burnt area in 2001 in the European Mediterranean region (source DG AGRI-FI)

Consequently, the fire events recorded into the database reduced to the follows:

Table 5.4: Number of forest fire in the database greater than 50 hectares occurred between May and October.

Year	SPAIN	FRANCE	ITALY
1989	1131	90	93
1990	622	45	407
1991	531	12	194
1992	213	16	191
1993	160	49	549
1994	423	42	297
1995	380	36	126
1996	177	16	149
1997	301	36	254
1998	268	40	0
1999	161	41	0
2000	0	29	0

Considering the results contained in the reconstructed database and considering the fire events distribution, it has been decided to focus the entire analysis only over the entire Spanish territory instead of the entire Mediterranean region. The follow table (table 5.5) reports the data events contained by the European Fire Database grouped by regions and year. It is noticeable that, during some years, some regions did not provided information regarding forest fire data events.

Table 5.5: For each region is reported in which year forest fire data events are registered. The xxxx sign means no data available for that year.

ES1 NOROESTE												
ES11 Galicia												
ES111 A Coruña	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
ES112 Lugo	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
ES113 Ourense	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
ES114 Pontevedra	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
ES12 Principado de Asturias												
ES120 Asturias	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
ES13 Cantabria												
ES130 Cantabria	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000

ES2 NORESTE												
ES21 País Vasco												
ES211 Álava	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
ES212 Guipúzcoa	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
ES213 Vizcaya	1989	1990	1991	1992	1993	xxxx	1995	1996	1997	1998	1999	2000
ES22 Comunidad Foral de Navarra												
ES220 Navarra	1989	1990	1991	1992	1993	1994	xxxx	xxxx	xxxx	xxxx	xxxx	xxxx
ES23 La Rioja												
ES230 La Rioja	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
ES24 Aragón												
ES241 Huesca	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
ES242 Teruel	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
ES243 Zaragoza	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000

ES3 COMUNIDAD DE MADRID												
ES30 Comunidad de Madrid												
ES300 Madrid	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000

ES4 CENTRO (E)												
ES41 Castilla y León												
ES411 Ávila	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
ES412 Burgos	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
ES413 León	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
ES414 Palencia	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
ES415 Salamanca	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
ES416 Segovia	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
ES417 Soria	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
ES418 Valladolid	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
ES419 Zamora	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
ES42 Castilla-La Mancha												
ES421 Albacete	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
ES422 Ciudad Real	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
ES423 Cuenca	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
ES424 Guadalajara	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
ES425 Toledo	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
ES43 Extremadura												
ES431 Badajoz	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
ES432 Cáceres	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000

ES5 ESTE												
ES51 Cataluña												
ES511 Barcelona	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
ES512 Girona	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
ES513 Lleida	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
ES514 Tarragona	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
ES52 Comunidad Valenciana												
ES521 Alicante / Alacant	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
ES522 Castellón / Castelló	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
ES523 Valencia / València	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
ES53 Illes Balears												
ES530 Illes Balears	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000

ES6 SUR												
ES61 Andalucía												
ES611 Almería	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
ES612 Cádiz	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
ES613 Córdoba	1989	1990	xxxx	1992	1993	1994	1995	1996	1997	1998	1999	2000
ES614 Granada	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
ES615 Huelva	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
ES616 Jaén	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
ES617 Málaga	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
ES618 Sevilla	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
ES62 Región de Murcia												
ES620 Murcia	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
ES63 Ciudad Autónoma de Ceuta												
ES630 Ceuta	xxxx	xxxx	1991	xxxx	xxxx	xxxx	xxxx	1996	xxxx	xxxx	xxxx	xxxx
ES64 Ciudad Autónoma de Melilla												
ES640 Melilla	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000

ES7 CANARIAS												
ES70 Canarias												
ES701 Las Palmas	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
ES702 Santa Cruz de Tenerife	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000

Finally, the total number of forest fire events available for the testing of the analysed indices was 4367 distributed all over 11 years.

5.3 Satellite sensor data

The advantages in using remote sensing applications for forest fire risk assessment have been discussed in chapter 4. The use of satellite sensor data permits to monitor the conditions of a particular large area more frequently than using ground observations, which are not always practicable or able to cover wide areas. Moreover, the possibility to have daily data permits better control of the fluctuations of the environment and, hence, better interpretation of potential status of risk.

5.3.1 Normalized Difference Vegetation Index

The Vegetation Index was introduced to quantify the concentrations of green leaf vegetation around the globe. The distinct colours, wavelengths, of visible and near-infrared sunlight reflected by the plants were observed to determine the density of greenness over a territory. During the day, sunlight strikes plants which absorb certain wavelengths and reflect others. The pigment in plant leaves, the chlorophyll, strongly absorbs visible light (from 0.4 to 0.7 µm) for use in photosynthesis. The cell structure of the leaves, on the other hand, strongly reflects near-infrared light (from 0.7 to 1.1 µm). The more leaves a plant has, the more these wavelengths of light are affected, respectively.

The Normalized Difference Vegetation Index, NDVI, is one of the most commonly used vegetation index. The NDVI is derived from the visible and near-infrared light reflected by vegetation according to Rouse (Rouse et al. 1974):

$$\mathrm{NDVI}= \frac{\mathrm{NIR} - \mathrm{VIS}}{\mathrm{NIR} + \mathrm{VIS}} = \frac{\mathrm{Ch2} - \mathrm{Ch1}}{\mathrm{Ch2} + \mathrm{Ch1}}$$

Healthy vegetation absorbs most of the visible light that hits it, and reflects a large portion of the near-infrared light. Unhealthy or sparse vegetation reflects more visible light and less near-infrared light. From construction, NDVI values always result in a number ranging from minus one to plus one (-1 to +1); a zero value means no vegetation and a value close to +1 indicates the highest possible density of green leaves.

It was demonstrated that the more a plant is absorbing visible sunlight, the more it is photosynthesizing, and the more it is being productive. Conversely, the less sunlight the plants absorbs, the less it is photosynthesizing, and the less it is being productive. Accordingly, NDVI values were studied in order to establish the growing conditions for the vegetation in a given region for a given period of the year. A decrement in the values of NDVI was interpreted, among other disturbances, as a reduction in plant growth due to a lack in precipitation, and as an indicator of drought.

Following these considerations, different works have been achieved by using NOAA-AVHRR NDVI data in the vegetation monitoring context (Belda and Melia 2000, Simoniello et al. 2002, Gurgel and Ferreira 2003). In the monitoring of the vegetation status to estimate the risk of forest fires maps of risk at local or continental scale are published daily (Oldford et al. 2002, San-Miguel-Ayanz et al. 2002). The NOAA satellites give the possibility to have wide coverage at high coverage frequency, essential requirement in order to execute studies at European level. Thus, the extension of the data provided permits to consider, at the same time, different vegetation environments inside a province, a country or a continent (Duchemin 1999). Nevertheless, the available information needs to be carefully interpreted taking into consideration also the ground information. Different countries have different varieties of vegetation presenting different behaviours depending on latitude, longitude and altitude. For this reason the possibility to extend results derived by the use of NDVI from local to European level has to be carefully evaluated. Moreover, as for other satellite products, the presence of clouds, atmospheric variability and bidirectional effects introduce noises in the resulting products (Goward et al. 1991, Chappell et al. 2001). The application of a reprocessing procedure and of a composite method in order to reduce the visibility of these noises resulted compulsory.

5.3.2 Available images

The study archive of NOAA-AVHRR images belonged to the Monitoring Agriculture with Remote Sensing, MARS, unit of the DG-JRC, Ispra, Italy. In 2002, the entire archive was reprocessed by using the SpacePC+ software (RNA-project) with the objective to obtain a consistent large archive of images (Piccard et al. 2002). In fact, over the years, the raw AVHRR data were delivered by different providers and, at the same time, processed with different software. The reprocessing chain consisted in calibration of the bands, atmospheric corrections and quality controls to permit the creation of a consistent dataset of NOAA-AVHRR images covering a lapse of time starting from 1989 to 2000. Atmospheric correction and radiometric calibration using post-flight coefficients were applied to the raw NOAA-AVHRR optical bands to obtain reflectance values from which the NDVI was computed (Tanre et al. 1990).

The reprocessing of the NOAA-AVHRR archive delivered three different kinds of product, called levels. Level3 product refers to daily composites images at 1.1 Km^2 of resolution. Level4 product refers to daily NDVI, land surface temperature, scan angle and scene id images at 1.1 Km^2 and at 4.4 Km^2. Level5 refers to 10-day NDVI composites at 4.4 Km^2 and quick looks images, images that permit an immediate overview. The daily NDVI images could be considered as a degraded product consisted in a level4 (L4) product derived from the level3 (L3) mosaic. For each L4 pixel, the NDVI was computed by averaging all the land and non-cloudy L3 pixels contained in the corresponding 4x4 window. The mean value of each channel was made before the NDVI computation. The resulting resolution was 4.4 Km^2 and the adopted maps projection system was Albers Equal Area. After the NDVI computation, the reprocessing chain coded the NDVI values over one byte and fixed the range of possible values between 0 and 200, instead of -1 and +1. The pixels coding was the following:

If pixel was:

- sea and no cloud, NDVI value= 255,

- sea and cloud,	NDVI value= 254,
- sea and no data,	NDVI value= 253,
- land and cloud,	NDVI value= 252,
- land and no data,	NDVI value= 251,
- ch1 = 0 and ch2 = 0,	NDVI value= 0,
- land and no cloud,	$\text{NDVI value} = \text{round}\left(\frac{\text{ch2} - \text{ch1}}{\text{ch2} + \text{ch1}} * 200\right).$
- NDVI value lowers than 0,	NDVI value 0.

In the context of the present analysis the values of NDVI has been rescaled from 0 to 1 instead of using the range 0 to 200. This conversion was necessary in order to compare the obtained results with results from other studies.

5.3.3 Composite methods

Similarly to others satellite sensor data the resulting product was affected by the presence of noise as clouds, atmospheric variability and bidirectional effects. A direct look over the images was necessary to evaluate the entity of the noise. Lack in information was the consequence of the presence of these noises (figure 5.7). Therefore, a direct study on these images could result unsuitable. Different methodologies have been developed in order to eliminate or reduce this lack of information. These methodologies were mainly based on the composition of different NDVI images in a resulting one.

The widely used composite method is the Maximum Value Composite (MVC) technique proposed by Holben (Holben 1986). Based on the assumption that contaminations depress NDVI value, the MVC retains the highest NDVI value over a defined compositing period, usually from one week to one month. Nevertheless, various other composite methods have been developed in order to furnish better or alternative results that MVC. The Best Index Slope Extraction (BISE) technique proposed by Viovy (Viovy et al. 1992) is one of these. It tries to exclude spurious high values and to take into account of the vegetation phenology. It supposes that rapid, non persistent increases, or decreases, in NDVI are inconsistent with natural vegetation growth. Moreover, in 1997, Taddei (Taddei 1997) proposed a composite method called Maximum Value Interpolated (MVI) based over an interpolation of MVC values and designed to produce a composite image over 30 days. Another method based on the use of Fourier analysis was proposed by Roerink (Roerink et al. 2000).

During this study different composite methods were tested and evaluated. Nevertheless, different reasons led to adopt the MVC method not only because it is the most commonly used composite method, but also because it is relatively easy for computation. It provided results comparable to the other methods, especially because of the adopted resolution (4 Km^2). Moreover, it does not need any information from the future evolution of the NDVI values as i.e. the MVI required. The composite period adopted was fixed to ten days, since it was assumed that the vegetation phenology does not vary significantly in a relative short time. In order to have better results, the daily images used during the composition technique were cloud free as strongly recommended by Chen (Chen et al. 2003). The daily and MVC images were constantly monitored during the composite process to immediately exclude data with bad quality, i.e. too many clouds or strange values. Figure 5.8 presents an example of MVC image obtained. The improvement in the information before and after the composite method is clearly visible.

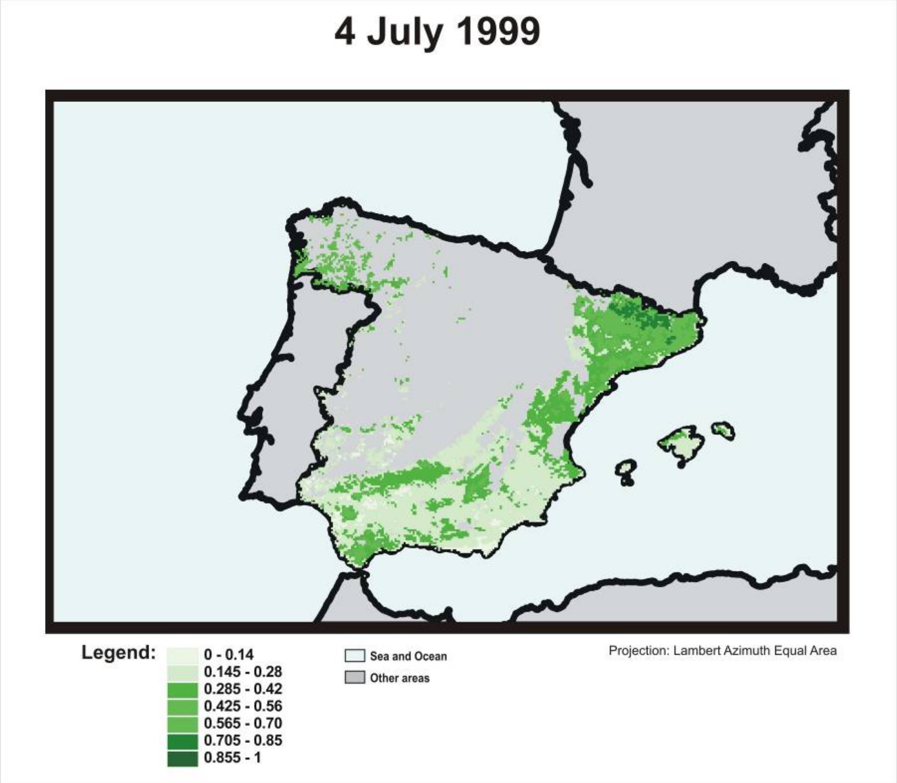


Figure 5.7: NDVI image for the 4 July, 1999

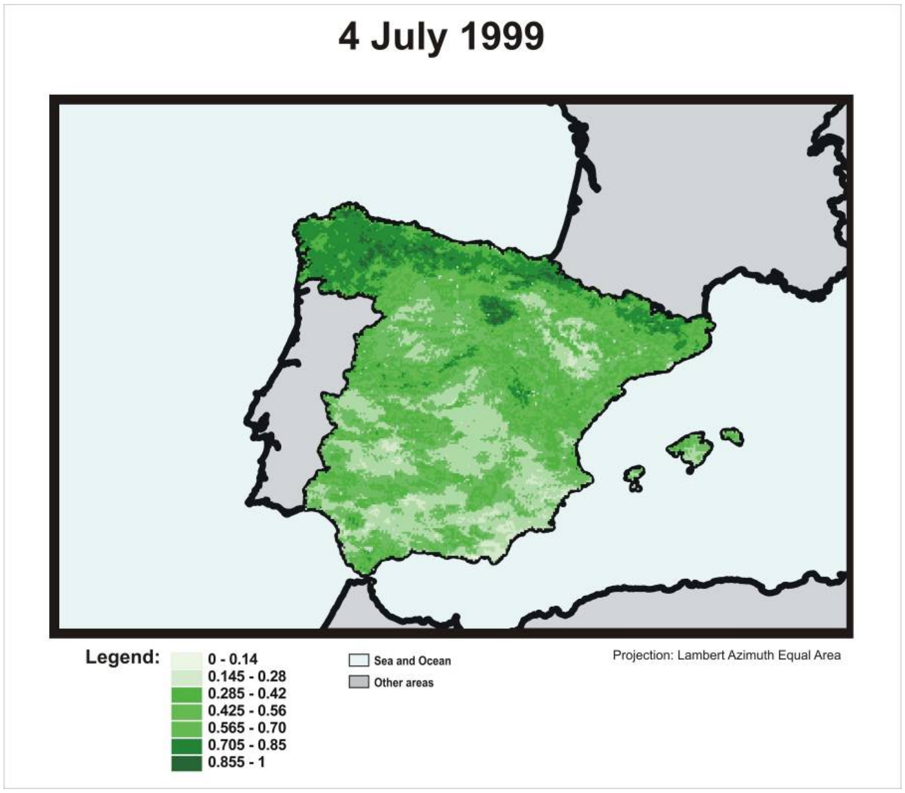


Figure 5.8: MVC-NDVI image for the 4 July, 1999 with temporal window of 10 days.

The available dataset of images covered the period between year 1989 and year 1999. Images from year 1994 were discarded because many of them were missing or presenting large amounts of errors and because the remaining images were not enough to produce reliable results. Following the consideration explained in Cap.5.2 the adopted images covered only the period from May to October. As a result, an archive of 1684 daily NDVI-MVC images was available for analysis (table 5.5).

Table 5.6: Number of considered MVC images grouped by year

Year	No of images
1989	169
1990	175
1991	175
1992	175
1993	152
1994	----
1995	175
1996	138
1997	175

1998	175
1999	175
2000	----
total	1684

5.3.4 NDVI derived indices

Several studies showed the correlation between NDVI and climate variables as rainfall and evapotranspiration over a wide range of environmental conditions (Kerr et al. 1989, Oindo and Skidmore 2002, Al-Bakri and Suleiman 2004, Sun et al. 2004). Studies demonstrated the robustness of NDVI as indicator of biomass and vegetation activity (Tucker 1979, White et al. 1997, Calvao and Palmeirim 2004, Granados-Ramirez et al. 2004, Maselli and Chiesi 2004, Wang et al. 2004). In the Mediterranean region, the trend of the NDVI values during the summer was associated to the trend of the vegetation water stress (Cihlar et al. 1991, Kogan 1997, Cesari et al. 2002, Song et al. 2004). Nevertheless, the trend of NDVI values is related not only to water stress. A relationship between NDVI and chlorophyll content was also demonstrated (Sims and Gamon 2003). The NDVI variation derives also by phenological status of the plant, atmospheric pollution, nutrient deficit, toxicity, plant disease and radiation stress. Assumptions can be acceptable for some species but prudence is necessary to generalize them to an entire ecosystem. According to this, studies were done and several others indices were introduced to improve the results obtained by using NDVI. Ceccato (Ceccato et al. 2001) demonstrated that the water content is better estimated by using the Equivalent Water Thickness (EWT) at leaf level. Estimation made possible by the introduction of an index that utilizes a combination of shortwave and near infrared as the Global Vegetation Moisture Index, GVMI (Ceccato et al. 2002, Ceccato et al. 2002).

Nevertheless, the aim of this study was not to demonstrate or evaluate a correlation between vegetation condition and NDVI value; existing researches deeply discussed about it (Ichii et al. 2002, Chuvieco et al. 2003, Chuvieco et al. 2004). Moreover, a precise estimation of the vegetation condition by using the considered NDVI data was retained as not applicable, since the pixel values were averaged at 4.4 Km resolution. Thus, this study would evaluate the assumption that a variation in value of the NDVI could be associated to a variation in risk of forest fire (Lopez et al. 1991, Illera et al. 1996, Gonzalez-Alonso et al. 1997, Leblon et al. 2001, Aguado et al. 2002, Maselli et al. 2003) and assessed the possibility to extend NDVI related information to a large territory. The analysis carried out considered the NDVI value together with the information collected in the European Forest Fire Information System. Nevertheless, the database structure and resolution did not permit to locate exactly a fire in the commune in which it occurred. Thus, it was decided to retain only one value as representative for the commune on a particular day. Considering the nature of the NDVI, the retained value was the one representative of the highest fire risk condition within that administrative boundary of the commune. Furthermore, since the NDVI values decrease by the burning of vegetation, in the case of a fire that occurred during the composite period, the MVC criterion retained values from the last days, in which the burned vegetation signal has been attenuated (Barbosa et al. 1998). Both assumptions lead to the worst possible conditions for the first exploratory analysis. As a consequence, if the present study ended without reliable results for this optimum case, no better result could be obtained by retaining other values of MVC for communes. During the analysis the mask of vegetation was applied to each MVC-NDVI image considered. As explained in the previous chapter, the use of a mask of vegetation permitted to retain only pixels corresponding to forests and semi-natural areas during the study. The analysis assessed the suitability of the use of NDVI, in particular of the use of MVC-NDVI, for forest fire risk. The capability of NDVI to discriminate the level of forest fire risk was evaluated. The hypothesis was that NDVI is a reliable indicator of fire risk if the statistical distribution of NDVI values on areas subjected to fires is significantly different from that on areas that do not suffer fires. It was demonstrated that number of forest fires tend to occur in areas having lower values of NDVI. Nevertheless, NDVI of areas surrounding the areas affected by fire was never considered for analysis. It could be possible that lower NDVI values may represent a normal behaviour of vegetation in the summer season and not be necessarily correlated to a fire occurrence. The extension of the study area together with the presence of different type of vegetation impose a deeply analysis of the definition of lower NDVI value. The concept of low values could be applied to a global or a local context. The first analysis was done by considering as lower a value close to the absolute minimum one, which in the case of the NDVI was 0. Nevertheless, this first assumption could be too general, since it was possible to observe that a lowest value assumed by northern area could correspond to about the highest value assumed in some place of the Mediterranean region. Thus, the definition of a low value was reduced to a local context by considering the evolution of the values during the years and during the entire study period. To study the evolution of values during the year it was considered the distance between the value in a considered place and the maximum value observed in the same place the previous days of the considered year; hence, lower values were represented by bigger difference to the maximum. To study the evolution of values during the entire period of study the Relative Greenness was adopted. In this case, the definition of lower value was referred to a value close to the historical minimum one assumed in the retained period. In addition a new methodology based on the inter-annual variation of NDVI values was introduced and compared to the others. In particular, analysis referred to:

- Analysis of MVC-NDVI in an intra-annual context. This analysis evaluates how much a direct use of MVC-NDVI values helps in individuates areas most at high risk of forest fire.

- Analysis of the MVC-NDVI decrement in an intra-annual context. This analysis evaluates how much the slope of MVC-NDVI values during the year is an indicator of areas most at high risk of forest fire. This methodology takes into consideration of the value assumed by a commune and its yearly maximum value.

- Analysis of Relative Greenness in an intra-annual context. This analysis evaluates how much the use of MVC-NDVI values helps in individuates areas most at high risk of forest fire. The RG methodology evaluates the MVC values considering them in a relative context. Each MVC value is re-scaled by considering the maximum and minimum value assumed by the pixel during the entire study time series.

- Analysis of MVC-NDVI in an inter-annual context, the Dynamic Relative Greenness Index. This analysis evaluates how much the use of MVC-NDVI values in an inter-annual context helps in individuates areas most at high risk of forest fire. The DRGI methodology re-scaled the MVC values by considering the maximum and minimum values assumed by the pixel in the same day during the entire study time series.

5.3.4.1 MVC-NDVI analysis

This analysis evaluates how much a direct use of MVC-NDVI values helps in individuates areas most at high risk of forest fire. This analysis considered the MVC-NDVI values directly with the hypothesis that an observed value close to 0 was an indicator of a higher level of forest fire risk and an observed value close to 1 was indicator of a lower level of risk.

5.3.4.2 MVC-NDVI decrement analysis (DIFF)

This analysis evaluates how much the slope of MVC-NDVI values during the year is an indicator of areas most at risk of forest fire. This methodology takes into consideration of the value assumed by a commune and its yearly maximum value. The objective was to investigate the relation of the decrement of the NDVI from the beginning of the fire season (May) with the risk of forest fires. The hypothesis was that the risk was linked to the difference between the yearly maximum value and the actual value; thus, higher the difference higher the risk. For this reason, the computation of the maximum value was done on a daily basis. For each day and for each year, the difference index, DIFF, was computed as follow:

$$DIFF_i = ND_{io} - ND_{max}$$

Where:

i = Considered day;

ND_io = MVC-NDVI value for the considered day;

NDmax = Maximum MVC-NDVI value observed starting from the beginning of the fire season (May).

The maximum value was established for each pixel dynamically. Each day, a commune assumed a value equal to the difference between its maximum value until that day and the actual one. If the actual value was bigger than the maximum, it became the new maximum since then. According to that, the DIFF values assumed only positive values. The justification on using a dynamical computation of the maximum value for each pixel followed the analysis of the variability of the NDVI. Past studies considered the value at the beginning of the fire season as the maximum one; however, it was observed that some areas reached their maximum later than this date.

5.3.4.3 Relative Greenness Index analysis (RGI)

The Relative Greenness, RG, methodology evaluates the MVC values considering them in a relative context. Each MVC value is re-scaled by considering the maximum and minimum value assumed in the entire study period. Burgan *et al.* (1998) proposed the use of the Relative Greenness (RG) to determine departure from the normal greenness in a region. This departure would show if an area was more or less green as compared to its range of variation. The RG compares the NDVI value on a given pixel with its overall historical maximum and minimum value. The maximum and minimum values, ND_{max} and ND_{min}, respectively, are constant for all the study period.

A Relative Greenness image was compute for each day as follow:

$$RG(i) = \frac{ND_o(i) - ND_{min}}{ND_{max} - ND_{min}} * 100$$

Where:

i = considered day;

$ND_o(i)$ = observed MVC-NDVI value;

ND_{max}, ND_{min} = historical maximum, minimum, of MVC-NDVI values over the studied time period.

Each day, each pixel of a RG image indicates how much the observed value for that pixel is close to its absolute minimum value. Thus, the 0 value is assumed when a pixel is equal to its minimum, while the value 1 is assumed when it is equal to its maximum. Consequently, the RG range is from 0 to 1 where a value close to 0 is linked to a high level of risk.

5.3.4.4 Dynamic Relative Greenness Index analysis (DRGI)

This analysis evaluates how much the use of MVC-NDVI values in an inter-annual context helps in individuates areas most at high risk of forest fire. Meanwhile it was possible to find several works based on the study of the evolution of NDVI during a year, the inter-annual variability of the NDVI has never been extensively taken into account. Gurgel and Ferreira (Gurgel and Ferreira 2003) found a good connection between the inter-annual variability of NDVI and climate; however, the study was done in Brazilian territory.

A novel methodology for the assessment of fire risk was developed. It was based on the assumption that it was possible to estimate forest fire risk by considering the inter-annual variability of the vegetation status. The new index was referred to as Dynamic Relative Greenness Index, DRGI. It considered the inter-annual variability of the NDVI on a precise location within the study region. Accordingly, for each day of the year, a daily minimum and maximum value, ND_{max} and ND_{min}, were computed.

The DRGI for day ‘i’ was the follows:

$$DRGI(i) = \frac{ND_o(i) - ND_{min}(i)}{ND_{max}(i) - ND_{min}(i)} * 100$$

Where, for each pixel:

i = day;

$ND_o(i)$ = observed MVC-NDVI value;

$ND_{max}(i)$, $ND_{min}(i)$ = daily historical maximum, minimum of MVC-NDVI.

It was assumed that low values of DRGI, i.e. daily values close to its period minimum, would be correlated to a situation of high risk of forest fire. Thus, DRGI range was from 0 to 1 where a value close to 0 was linked to a high level of risk.

5.4 Meteorological data

The role played by meteorological conditions in the forest fire ignition and evolution is commonly recognised. Meteorological conditions are directly involved in driving a fire ignition into a so called large fire. Most of the yearly damages caused by forest fire are strictly dependent by those large fires. As described in chapter x the fire propagation could be linked to solar radiation, air temperature, humidity, rainfall and wind conditions. Several methods of fire danger assess based on the estimation of weather condition have been developed. In this chapter one of the most used meteorological indexes, the Fire Weather Index, is introduced.

5.4.1 Fire Weather Index (FWI)

In 1970, after four years of efforts, the Canadian Forestry Service developed the Canadian Forest Fire Weather Index, FWI, system with the aim to estimate the danger of forest fire. The first FWI system was referred to a standard pine fuel type but, successively, it has been extended to a general measure of forest fire danger. The system structure is made by different components collecting information about fuel moisture, rate of fire spread, fuel consumption and fire intensity (figure 5.9). The total number of components is six. Each component is determined daily on the basis of information collected from noon local standard time weather readings. The components have been classified as related to fuel moisture information or fire behaviour information.

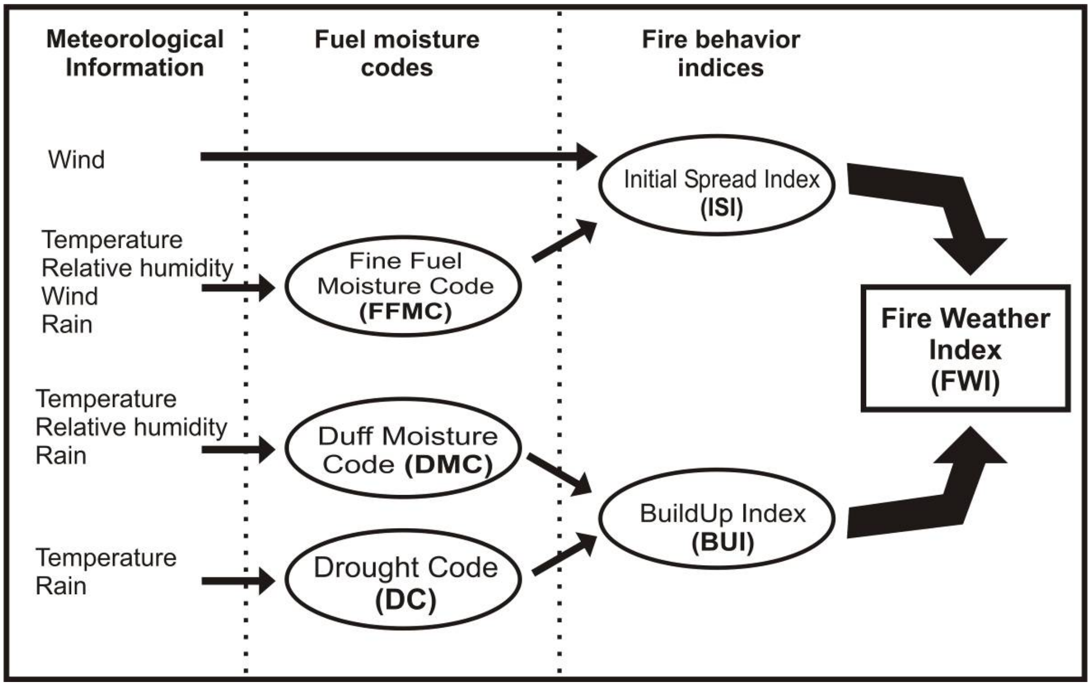


Figure 5.9: The Fire Weather Index structure

The technical report "Development and structure of the Canadian Forest Fire Weather Index System" (Canadian Forestry Service 1987) presented the following definitions for the FWI System components:

- **Fine Fuel Moisture Code:** The Fine Fuel Moisture Code (FFMC) is a numeric rating of the moisture content of litter and other cured fine fuels. This code is an indicator of the relative ease of ignition and the flammability of fine fuel.
- **Duff Moisture Code:** The Duff Moisture Code (DMC) is a numeric rating of the average moisture content of loosely compacted organic layers of moderate depth. This code gives an indication of fuel consumption in moderate duff layers and medium-size woody material.
- **Drought Code:** The Drought Code (DC) is a numeric rating of the average moisture content of deep, compact organic layers. This code is a useful indicator of seasonal drought effects on forest fuels and the amount of smouldering in deep duff layers and large logs.
- **Initial Spread Index:** The Initial Spread Index (ISI) is a numeric rating of the expected rate of fire spread. It combines the effects of wind and the FFMC on rate of spread without the influence of variable quantities of fuel.
- **BuildUp Index:** The BuildUp Index (BUI) is a numeric rating of the total amount of fuel available for combustion. It combines the DMC and the DC.
- **Fire Weather Index:** The Fire Weather Index (FWI) is a numeric rating of fire intensity. It combines the Initial Spread Index and the BuildUp Index. It is suitable as a general index of fire danger throughout the forested areas of Canada.

- **Daily Severity Rating:** The Daily Severity Rating (DSR) is a numeric rating of the difficulty of controlling fires. It is based on the Fire Weather Index but more accurately reflects the expected efforts required for fire suppression.

It is out of the scope of this thesis to describe more in detail the elements constituting each component and the way in which they are combined.

Several works applied the FWI System to the European territory, even thought the FWI System was originally developed for forest fire danger estimation of the Canadian territory. In particular, the Mediterranean region has been investigated and comparisons between FWI and others meteorological indices of risk were carried out (Bovio and Camia 1998, Camia et al. 1999, Viegas et al. 2000). Nevertheless, one of the topics of the present work is to evaluate the performance of the FWI over the entire Spanish territory and to compare these performances with the ones obtained by using indices derived by remote sensing. In this way, it would be evaluated the weight meteorological condition have on the ignition of large fire compared to the weight given by the vegetation conditions estimated by the NDVI.

5.4.2 Available data

The available FWI information was derived from a database implement inside the MARS, Monitoring Agriculture by Remote Sensing, action. The MARS, started in 1988, was designed to apply emerging space technologies for providing independent and timely information on crop areas and yields (http://mars.jrc.it). This action is currently part of the AGRIFISH unit of the European Commission Joint Research Centre of Ispra, Italy.

The available meteorological database permitted to dispose of homogeneous and continuous data. It consists of daily meteorological measures recorded at 12:00 a.m. from about 360 ground weather stations throughout Europe. The measures have been spatially interpolated over 1389 square grid cells of 50 km^2. Hence, a daily FWI image was available for all the fire campaign period during the retained years; period exactly matched to the considered in the vegetation indices study.

The information extracted by the MARS database referred to the daily FWI values assumed by each of the 50x50 Km cell contained in the Spanish territory (figure 5.10).

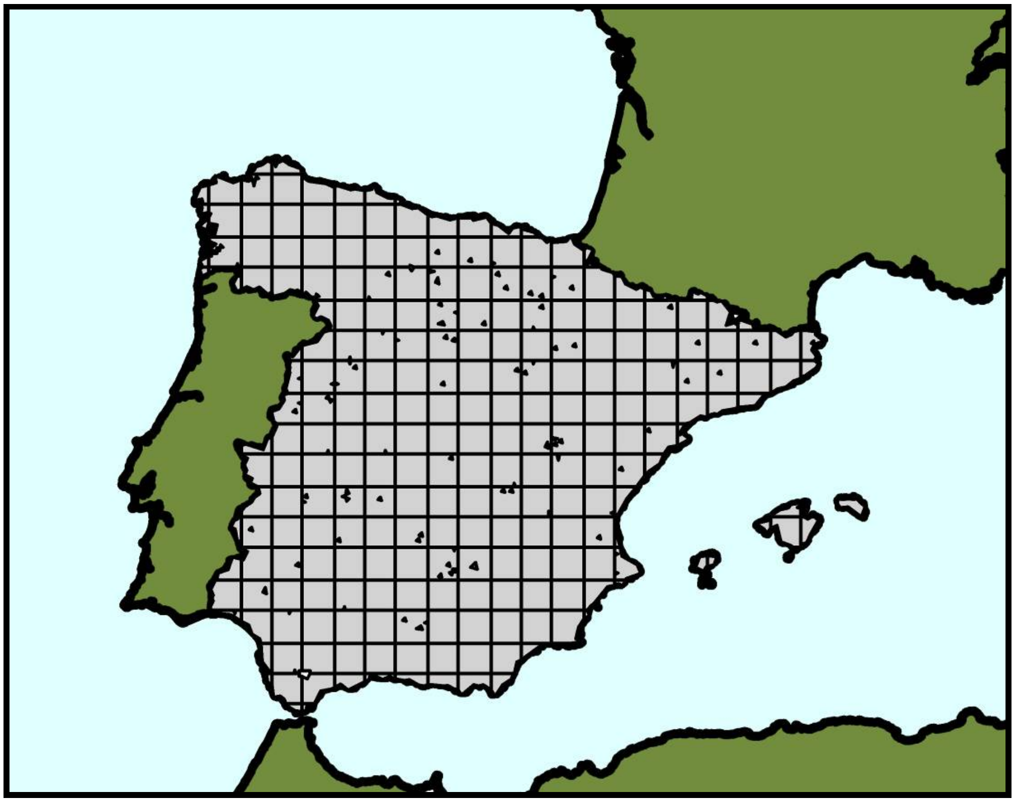


Figure 5.10: 50x50 Km square cells contained in the Spanish territory

As a consequence of the fire data events database resolution, the FWI information has been reclassified at a communal level, following a procedure similar to the adopted in the NDVI analyses. For every day, if a commune was crossed by more than one grid cell, it was associated to the maximum observed FWI value. This value was representative of the maximum observed level of risk derived by the FWI information; since higher level of FWI has been related to high level of forest fire risk. The information contained in the FWI database was extracted and converted into an FWI image. Thus, a FWI image was available for each day of the considered period of analysis.

5.5 Territory masks

In order to compensate the high variability of indices values all over a wide territory, two different masks have been developed and applied during analysis. The first mask referred to the analysis of the different kinds of vegetation available in the territory. The second mask was strictly related to the NDVI variability.

5.5.1 Vegetation mask

A mask of vegetation was introduced with the aim to retain only pixels corresponding to forests and semi-natural areas during the study of NDVI derived indices. Pixels corresponding to artificial surfaces, agricultural areas and wetlands were discarded because of a risk to introduce mistakes, i.e. irrigation crops or harvested crops would present artefacts in the normal evolution of vegetation related variables.

The mask of vegetation was derived from the CORINE Land Cover Database (Cap. 5.5.1.1) retaining only a restricted part of the classes (table 5.7) and re-sampling them to 4.4Km^2 spatial resolution (figure 5.11).

Table 5.7: Retained classes

2. Agricultural areas	**2.4. Heterogeneous agricultural areas**	2.4.3. Land principally occupied by agriculture, with significant areas of natural vegetation 2.4.4. Agro-forestry areas
3. Forests and semi-natural areas	**3.1. Forests**	3.1.1. Broad-leaved forest 3.1.2. Coniferous forest 3.1.3. Mixed forest
	3.2. Shrub and/or herbaceous vegetation association	3.2.1. Natural grassland 3.2.2. Moors and heathland 3.2.3. Sclerophyllous vegetation 3.2.4. Transitional woodland shrub
	3.3. Open spaces with little or no vegetation	3.3.3. Sparsely vegetated areas

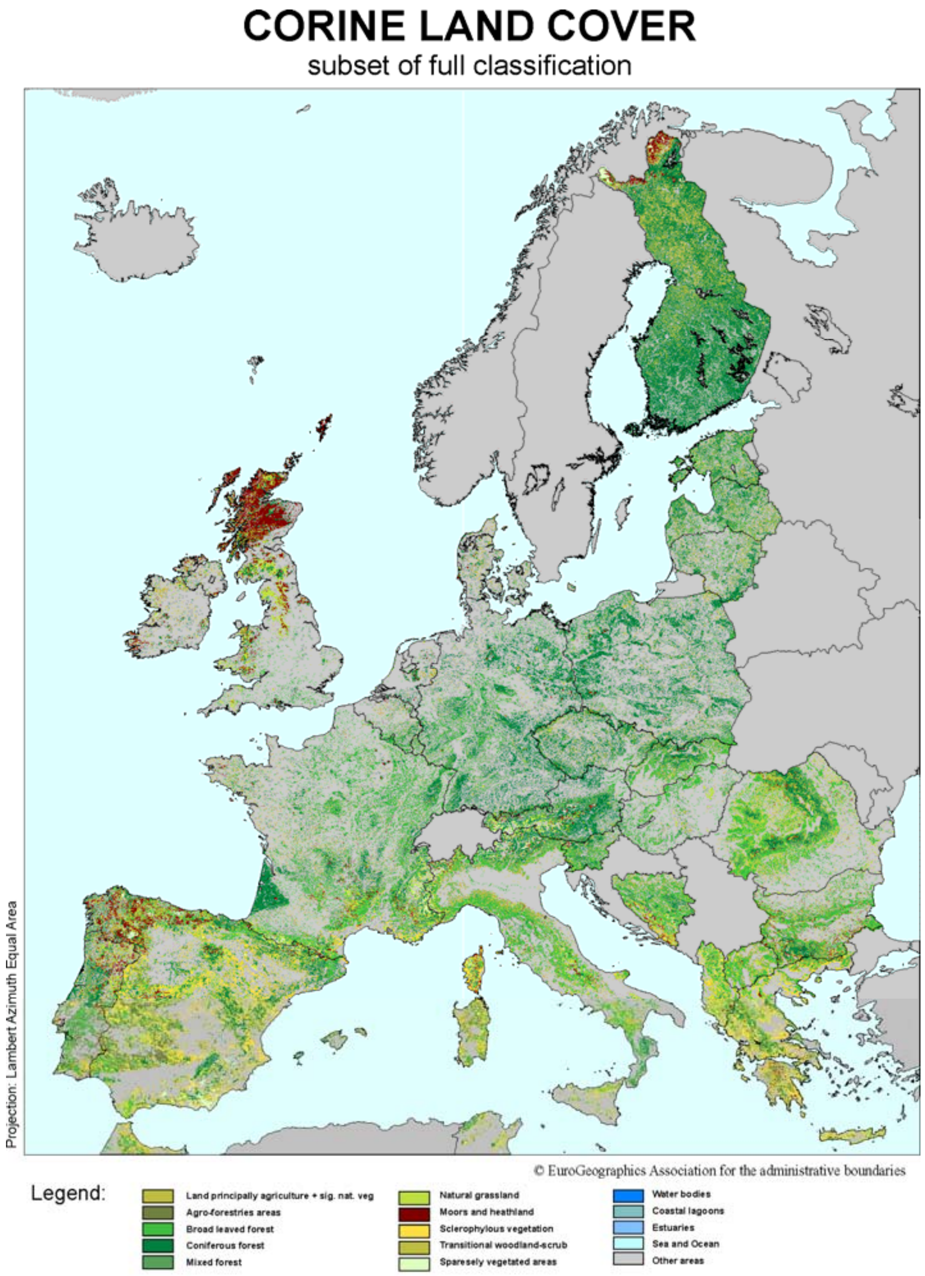


Figure 5.11: The retained subset of the CORINE Land Cover Database in the adopted mask of vegetation.

5.5.1.1 CORINE Land Cover Project

The European Commission is the main body in charge of preserving European environmental condition. A reliable knowledge of the environment, like the actual and future state and the reasons of changing, has been required by the European Commission to determine and implement environmental policies and programmes accurately. This information is required at different levels, Community, Country and regional. As a consequence, and following a decision of the Council of the Ministers, an experimental project for gathering, coordinating and ensuring the consistency of information on the state of the environment and natural resources in the Community was initiated in 1985. The project was named CORINE, Coordination of information on the environment. The CORINE project focussed on a collection, coordination, organization and validation of information related to the environmental conditions for all the Member states. One of the major tasks in the framework of the CORINE programme was the land cover project. A team of national experts, geographers, photo interpreters and cartographers, worked on satellite images computer-aided interpretation, digitalization and integration of national results to produce the CORINE land cover database (European Commission 1993). The project initially comprised 12 countries for a total of about 2.3 millions Km^2 of covered area with a minimum mapping unit size of 25 ha. The land cover nomenclature presented 44 classes grouped in three levels of detail. The main level categories were artificial surfaces, agricultural areas, forests and semi-natural areas, wetlands and water bodies (table 5.7). The original project has been updated several times during last years, following the methodologies recommended in the addendums to the official technical guide (Perdigao and Annoni 1997, Bossard et al. 2000). In particular, the major update referred to the introduction in the project of new European accession Countries (figure 5.12).

Table 5.8: CORINE land cover nomenclature

1. Artificial surfaces	**1.1. Urban fabric**	1.1.1. Continuous urban fabric 1.1.2. Discontinuous urban fabric
	1.2. Industrial, commercial	1.2.1. Industrial or commercial units and transport units 1.2.2. Road and rail networks and associated land 1.2.3. Port areas 1.2.4. Airports
	1.3. Mine, dump	1.3.1. Mineral extraction sites and construction sites 1.3.2. Dump sites 1.3.3. Construction sites
	1.4. Artificial non-agricultural vegetated areas	1.4.1. Green urban areas 1.4.2. Sport and leisure facilities
2. Agricultural areas	**2.1. Arable land**	2.1.1. Non-irrigated arable land 2.1.2. Permanently irrigated land 2.1.3. Rice fields
	2.2. Permanent crops	2.2.1. Vineyards 2.2.2. Fruit trees and berry plantations 2.2.3. Olive groves
	2.3. Pastures	2.3.1. Pastures
	2.4. Heterogeneous agricultural areas	2.4.1. Annual crops associated with permanent crops 2.4.2. Complex cultivation 2.4.3. Land principally occupied by agriculture, with significant areas of natural vegetation 2.4.4. Agro-forestry areas
3. Forests and semi-natural areas	**3.1. Forests**	3.1.1. Broad-leaved forest 3.1.2. Coniferous forest 3.1.3. Mixed forest
	3.2. Shrub and/or herbaceous vegetation association	3.2.1. Natural grassland 3.2.2. Moors and heathland 3.2.3. Sclerophyllous vegetation 3.2.4. Transitional woodland shrub
	3.3. Open spaces with little or no vegetation	3.3.1. Beaches, dunes, and sand plains 3.3.2. Bare rock 3.3.3. Sparsely vegetated areas 3.3.4. Burnt areas 3.3.5. Glaciers and perpetual snow
4. Wetlands	**4.1. Inland wetlands**	4.1.1. Inland marshes 4.1.2. Peatbogs
	4.2. Coastal wetlands	4.2.1. Salt marshes 4.2.2. Salines 4.2.3. Intertidal flats
5. Water bodies	**5.1. Inland waters**	5.1.1. Water courses 5.1.2. Water bodies
	5.2. Marine waters	5.2.1. Coastal lagoons 5.2.2. Estuaries 5.2.3. Sea and ocean

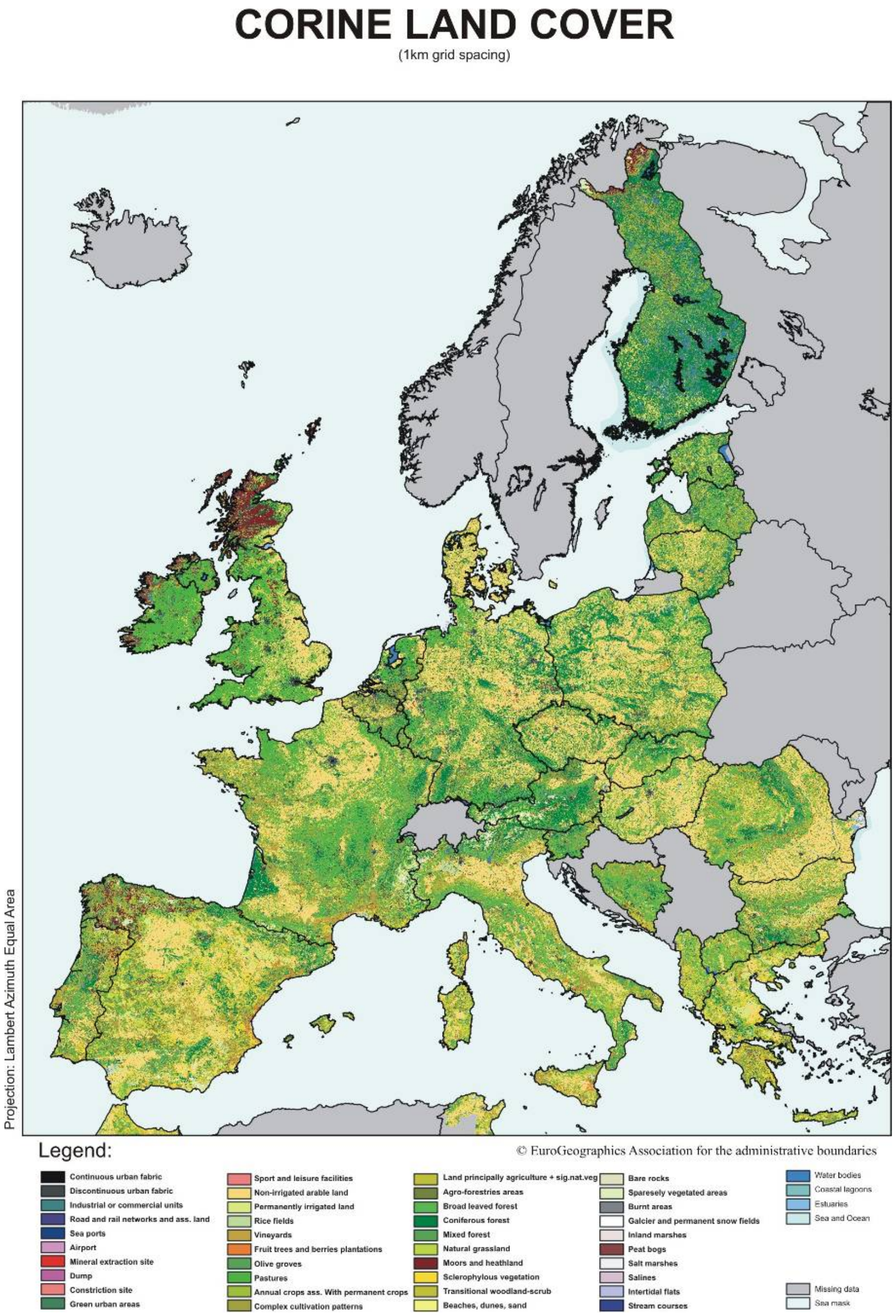


Figure 5.12: The CORINE Land Cover Database at 1 Km^2 spatial resolution

5.5.2 Territory division

In order to reduce the large variability of the NDVI values over entire Spain, the territory was divided according to the range of variation of the NDVI values. The statistical methods for the classification or ranging of interval/ratio data are several and one of the most common in cartography is the natural breaks method based on a subjective recognition of gaps in the distribution. This method, developed by George Jenks (Jenks and Caspall 1971), minimizes variation within classes and maximizes variation between classes. He suggested plotting the histogram of the data in order to highlight gaps. Thus, the histogram of the average NDVI values during the considered time series was plotted and, following the natural break method direction, a gap in the distribution was detected at NDVI average value equal to 0.55 (figure 5.13). As a result, the territory was divided in two different zones (figure 5.14). Zone 1 was characterised by pixels having average value bigger than 0.55 and zone 2 by pixels having average value lower than 0.55. It was observed that the typical Atlantic zone with slight water deficit during the summer was characterised by higher average values of NDVI and the typical Mediterranean zone having a lack of rain during the summer was characterised by lower average values of NDVI. In order to have a reliable comparison of the results coming from different indices, the mask of vegetation was applied both to the NDVI derived indices and to the FWI.

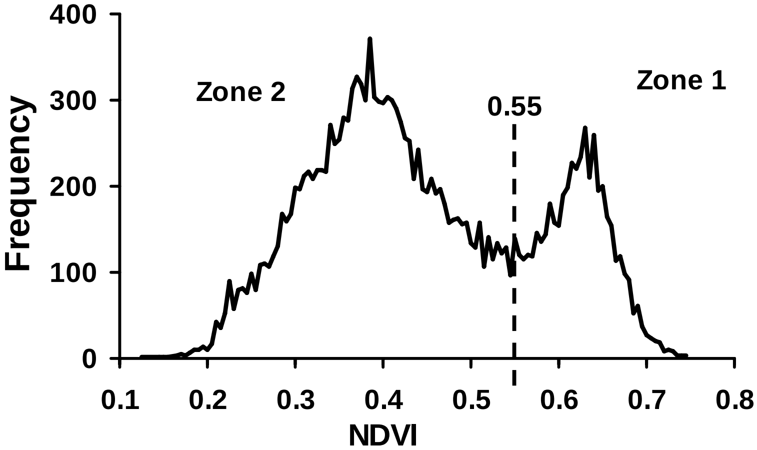


Figure 5.13: Histogram of the average NDVI values observed in the retained period. 0.55 represents the NDVI value considered as border between zone 1 and zone 2.

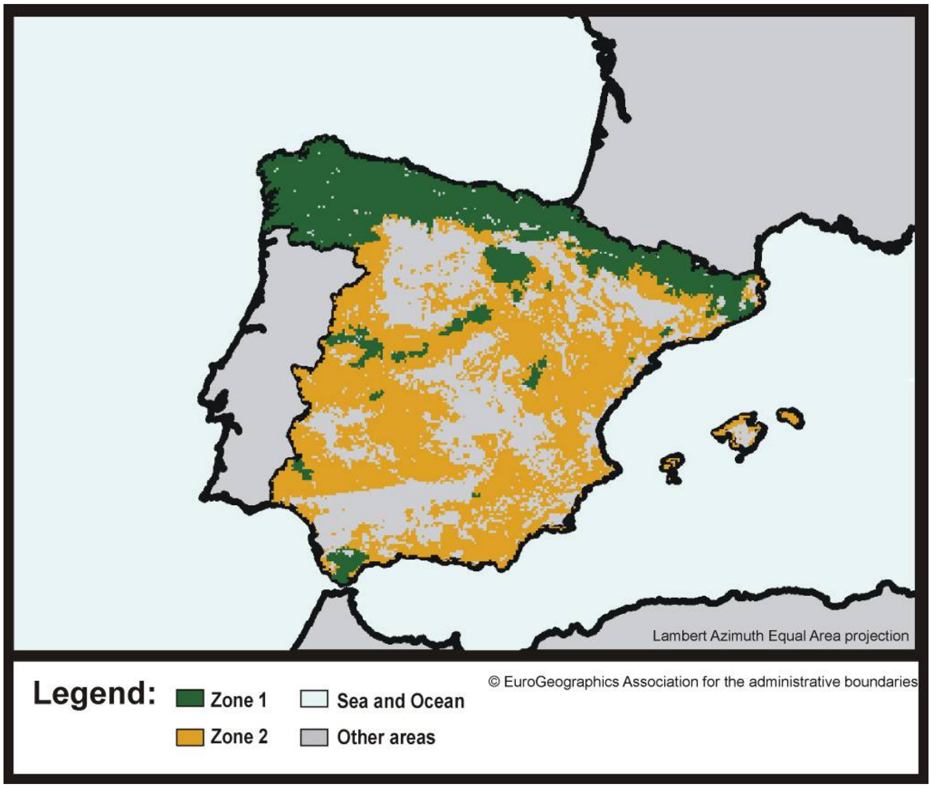


Figure 5.14: Territory division by considering the average values of the NDVI for the retained period.

5.6 *Qualitative approach*

The first analysis for each of the considered indices was based on a qualitative approach. This analysis was based on a graphical comparison of values collected from burnt areas with values collected all over the territory. The approach would verify the hypothesis that an area subject to forest fire, or at risk of forest fire, presents a value representative of a level of risk bigger than other areas. Thus, the obtained result should highlight a statistical difference in the distribution of values over burnt areas and all over the territory.

5.6.1 Method

Two different distributions of frequency were obtained for each of the considered indices of forest fire risk and for each of the two zones of Spain. The first distribution referred to the global distribution of values assumed during the entire period of study. For each day, the value presented by each commune was observed and retained. The second distribution referred to only values observed over a commune the day of a fire. Each day, the database of event had been queried in order to establish the list of commune subject to fire occurrence in that day. Thus, the values observed over those communes were collected. The two set of values were plotted in order to obtain a graph of the relative frequency of values in the two cases. To better evaluate the different distributions of values it were collected values not only considering entire study period, but also month by month. Thus, for each year information regarding a particular month was extracted and collected in the corresponding set of data. This second analysis permitted a qualitative analysis of the behaviour of the index in a monthly point of view. The aim was to compare not only the global but also the monthly results. This permitted to observe if an index produced better results in some months than in others.

Even though this analysis has been already applied, it does not permit a precise evaluation of the obtained results and moreover, it does not permit a comparison of results obtained by different indices of risk. Nevertheless, visible differences in the distributions of values are a first indicator of a statistically difference between the values assumed by burnt area compared to other areas.

5.7 Statistical approach

As presented by previous chapters, an index of fire risk can be obtaining from meteorological, vegetation or non natural parameters. Different indices were developed on the basis of experiments and experience over particular area. As a consequence, the range of values they present could be quite different. All these conditions face the problem to evaluate the performance of each index in a method not dependent by the index and that allows their comparison. The qualitative approach permits a general evaluation of the obtained results. Thus, a precise methodology of comparison is necessary to be adopted in order to compare results obtained by using different indices of risk.

It was decided to adopt a comparison methodology based on the use of the “performance index” as introduced by Mandallaz (Mandallaz and Ye 1997). The performance index permits to evaluate the performance of an index of risk on a daily basis. Every day, the information obtained by using the index of risk is compared to the information obtainable by using arbitrary values among the observed. Mandallaz retained the use of the randomness, referred as pure chance, the only method that could be fitted to all data sets and, that allows historical comparisons. Thus, the performance index evaluates the value added by using the index of risk instead of the pure chance. In his article, Mandallaz suggested the computation of four indices on a daily basis:

$$I_p = \sum_{i=1}^{N} \mathrm{rank}(z_i) I_i ; \qquad I_{random} = \frac{d(N+1)}{2}$$

$$I_{max} = \frac{d(2N+1-d)}{2} ; \qquad I_{ratio} = \frac{I_p - I_{random}}{I_{max} - I_{random}} \in (0,1)$$

Where:

I_p = performance index;

I_{random} = random performance index;

I_{max} = max performance index;

I_{ratio} = ratio performance index;

z_i = value of risk assumed by commune i;

$rank(z_i) \in \{1,2,...,N\}$ = rank of the value z_i;

I_i = random indicator variable, 0 if there were no fires on commune i, 1 otherwise;

d = number of fires;

N = number of communes.

In particular:
The performance index represents the performance obtained by using a particular index of risk during day *i*.
The random performance index represents the performance obtained by using a random value of the index of risk during day *i*.
The max performance index represents the maximum obtainable value of performance during day *i*. It represents the ideal case in which all the fire occurred assuming the maximum observed values of risk.
The ratio performance index represents the obtained result of the performance index in a scale between 0 and 1; where the 1 value is representative of the best case and the 0 of the worst case.

5.7.1 Method

For each day, one value of risk from each considered commune was retained. As described previously, the retained value was the one representative of the major level of risk for the commune. Subsequently, a list of retained values was obtained by ordering them in an ascending numerical way. The rank, the position of that value inside the list of the observed values, of all the values assumed by burnt commune during day *i* were summed up to compute the performance index for day *i*. The best condition obtainable for a particular day was when the burnt communes assumed all the highest values present in the list of retained values. In other words, when all the fire events occurred assuming the highest observed values of risk. This optimal condition is represented by the max performance index and is reached when the performance index assumes this value in the considered day. The random performance index indicates the daily value that the performance index has to reach in order to have a performance of the analysed index of risk better than the randomness. Thus, the random performance index permits to evaluate the value added by using an index of risk instead of a pure chance. The ratio performance index scales the previous information over a scale between 0 and 1. It evaluates how much the index of risk under examination performs better than the pure chance. Since the range of values of the ratio performance index is the same for each analysed index of risk, it led an immediate comparison of the performances of different indices. All the values of the ratio index lower than 0 had been rounded to 0 because representative of condition in which the use of randomness was better than the use of the index.

The computation of the performance index has been adapted to the use with indices where a low value was indicator of a high level of risk, as for the MVC-NDVI. Consequently, in order to permit the comparison of the results the computed performance index became:

$$I_p = \sum_{i=1}^{N} \mathrm{rank}^*(z_i) I_i ;$$

Where:

z_i = NDVI value of the commune i;

$\mathrm{rank}^*(z_i) \in \{1,2,...,N\} = N - \mathrm{rank}(z_i) + 1$;

$\mathrm{rank}(z_i)$ = rank of z_i;

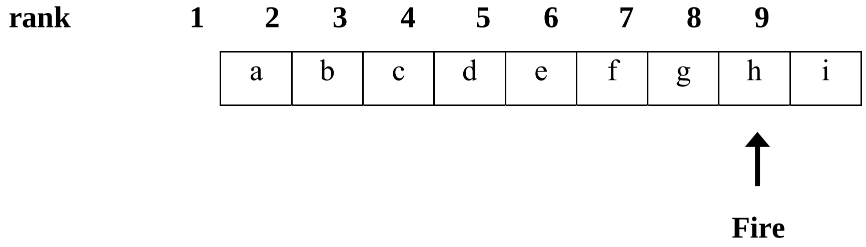
5.7.2 Examples

To better understand the use of the performance index adopted, following are reported three simple examples. For simplicity, it was assumed to have an area with only 9 communes. First of all, the values of risk relatives to each commune have to be collected and introduced in a list ordered in an ascending numerical way.

rank	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
	a	b	c	d	e	f	g	h	i

The observed values of the index of risk are reported by using letters because they are not important in the computation of the performance index. Only the position inside the matrix is important. Values having lower rank position present lower risk status than values having higher rank position.

- **Example 1:**



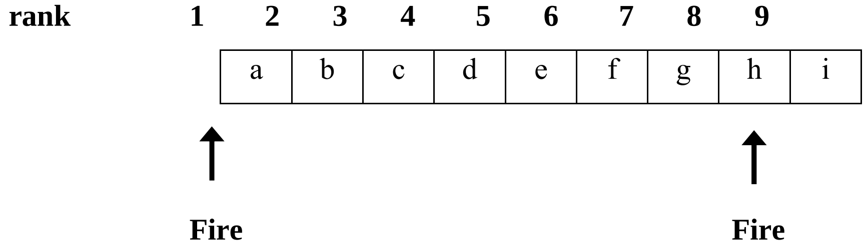
During a particular day, in presence of a fire occurred in a commune with value of risk equal to “i” and rank equal to 9, the corresponding indices of performances are:

$$I_p = \sum_{i=1}^{N} \mathrm{rank}(z_i) I_i = 9\,; \qquad I_{random} = \frac{d(N+1)}{2} = \frac{1(9+1)}{2} = 5$$

$$I_{max} = \frac{d(2N+1-d)}{2} = \frac{1(18+1-1)}{2} = 9\,; \qquad I_{ratio} = \frac{I_p - I_{random}}{I_{max} - I_{random}} = 1$$

The case in which a fire occurs assuming the highest observable value of the index of risk is considered as the best case. Here, the performance index assumes the maximum values possible, represented by I_{max} and, consequently, the ratio performance index presents the maximum value possible that is 1.

- **Example 2:**



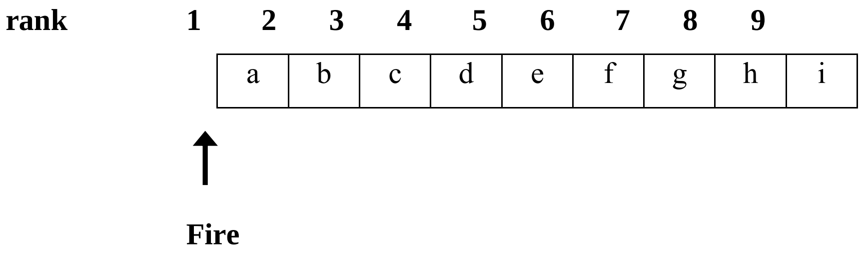
In the presence of two fires, one having the lowest possible value of risk and another one having the highest, the corresponding indices of performances became:

$$I_p = \sum_{i=1}^{N} \mathrm{rank}(z_i) I_i = 9 + 1 = 10\,; \qquad I_{random} = \frac{d(N+1)}{2} = \frac{2(9+1)}{2} = 10$$

$$I_{max} = \frac{d(2N+1-d)}{2} = \frac{2(18+1-2)}{2} = 17; \qquad I_{ratio} = \frac{I_p - I_{random}}{I_{max} - I_{random}} = 0$$

This case shows the capability of the performance index to evaluate an index of risk in a daily context. Even though one fire occurred assuming the highest values of risk the global result was influenced by the second fire; occurred assuming the lower value of risk. Thus, the global result obtained by the index was considered as not good since the performance index presents the same value than the random performance index.

- **Example 3:**



The last considered example takes into consideration of a fire occurred assuming the lowest observed value of the index of risk. The corresponding indices of risk are:

$$I_p = \sum_{i=1}^{N} \mathrm{rank}(z_i) I_i = 1; \qquad I_{random} = \frac{d(N+1)}{2} = \frac{1(9+1)}{2} = 5$$

$$I_{max} = \frac{d(2N+1-d)}{2} = \frac{1(18+1-1)}{2} = 9; \qquad I_{ratio} = \frac{I_p - I_{random}}{I_{max} - I_{random}} = 0$$

In this last case, the performance index results lower than the random performance index and the ratio performance index equals to zero. In this case, in fact, each value of the index chosen randomly would present better result than the observed one. This is the worst possible condition observable.

5.8 Software

A main point in a statistical analysis is the choice of the software to use to process the data. Even thought, this choice is often not deeply considered in the planning of certain analyses, the possibility to have powerful software gives a significant support to the entire process. In the present context, software able to process the huge amount of data available, more than 8000 images and about 4000 fire data events over a total of 6917 considered communes, in a reasonable lapse of time was a fundamental requirement. The software would be able to directly interact with database, like Oracle and Microsoft Access, to extract information for analysis. To best satisfy these requirements it was decided not to adopt already existent applications but to build proper new ones. In particular, it was used Java programming language to obtain them. This chapter briefly introduces the Java programming language, the Java Advanced Imaging, JAI, and the main classes developed.

5.8.1 JAVA

Java is a programming language object oriented developed by Sun Microsystems. Object oriented programming differs from others because a program is considered as a group of interacting objects. Each object is independent from others and it has to follow some precise rules to communicate to others. Java is well note for its potential to create programs able to run over internet, known as applet, and it has continued to grow both in popularity than in scope since its first release. Java is based on the C and C++ programming languages, differing from them in some important points. The main differences are that it is simple, sure, object oriented, platform independent and support multithreading.

5.8.2 Java Advanced Imaging

The Java Advanced Imaging, JAI, Advanced Programming Interface, API, further extends the Java platform by allowing sophisticated, high performance image processing to be incorporate into Java applets and applications. JAI implements a set of core image processing capabilities including image tiling, region of interest, and deferred execution. It also offers a set of core image processing operators including many common points, area, and frequency domain operators. JAI follows the Java run time library model, which means that it is platform independent. Implementations of JAI applications will run on any computer having a Java Virtual Machine. Moreover, like Java itself, JAI is totally object oriented. Thus, images and image processing operations are defined as objects. Jai supports complex image formats, including images of up to three dimensions and an arbitrary number of bands.

5.8.3 Classes developed

As described in the introduction, the use of Java programming language together with JAI API permitted to developed different classes able to load and process the available data. In particular, the adoption of methods built appositely for the considered images of this study permitted to decrease the time necessary to process the entire time series of images, about ten years of daily images, in an order of time of few minutes. The short time required for analysis together with the potentials of the Java programming language permitted to develop and testing different scenarios of study. It was possible to monitor the evolution of the values of a particular index of risk considering one day, one month, one year at time or the entire time series of ten years. This permitted to asses the performance of a particular index during the months and to evaluate the difference between a particular year and a different one. Following the principal classes developed have been briefly introduced and described.

- **ImageBILOp**: this class implements some operations necessary in order to use the adopted image format, band interleaved format (BIL), with Java. It permits to create new image instances, to load and store image file and corresponding header and map info files. It allows the reading and writing of all the parameters of an image;

- **GISImage**: this class implements all the operation to work with the images loaded with the ImageBILOp class. It permits to change the resolution of an image, to change the data values and to create a copy of a data image;

- **JAIUtil**: this class furnishes some extra functions to use on the images. It permits the application of threshold values and the creation of image masks in base to images of values passed;

- **CreateMVC**: this class permits the creation of MVC images in function of given variables. The image is in BIL format;

- **CreateDIFF**: this class permits the creation of DIFF images in function of given variables. The image is in BIL format;

- **CreateRGI**: this class permits the creation of RGI images in function of given variables. The image is in BIL format;

- **CreateDRGI**: this class permits the creation of DGRI images in function of given variables. The image is in BIL format;

- **CreateFWI**: this class permits the creation of FWI images in function of given variables. Every day, it extracts from a given database the FWI grid values and constructs a corresponding image in BIL format;

- **ComsValue**: this class permits to associate a univocal value to each commune of a particular country in function of given variables;

- **DailyImages:** this class takes each NDVI image, it applies the vegetation mask on it and it crops the image to the Spanish territory only;

- **ImageJPEG**: this class permits a direct conversion of a BIL image into a JPEG image. This permitted to dispose of a quick overview of any image created;

- **AverageTrend**: this class permits the plotting of the trend of the average value computed all over a particular area of the considered country in function of the variables given. The average trend could be computed considering one or more years at time;

- **IndexAnalysis**: this class permits to compute the histogram of the relative frequency distribution of the values of the considered index of risk. The computation could be done all over the territory or only considering a particular area in function of the given input variables;

- **RiskAnalysis**: this class permits to collect the value of a particular index of risk presents in a commune the day of a fire. Every day, it queried the database of fire event in order to make a list of commune having a fire in that particular day. Subsequently, it extracts the values of risk assumed by those communes and an histogram of the number of fires occurred assuming a determined value of risk is provided;

- **PerformanceIndex**: this class permits to compute all the performance indices for each day of the retained period and for each index of risk considered.

5.8.4 Classes diagrams

The follow figures reports a simple figure of the interaction amongst different classes.

Figure 5.15 reports the creation of the MVC dataset of images starting from the original NDVI dataset.

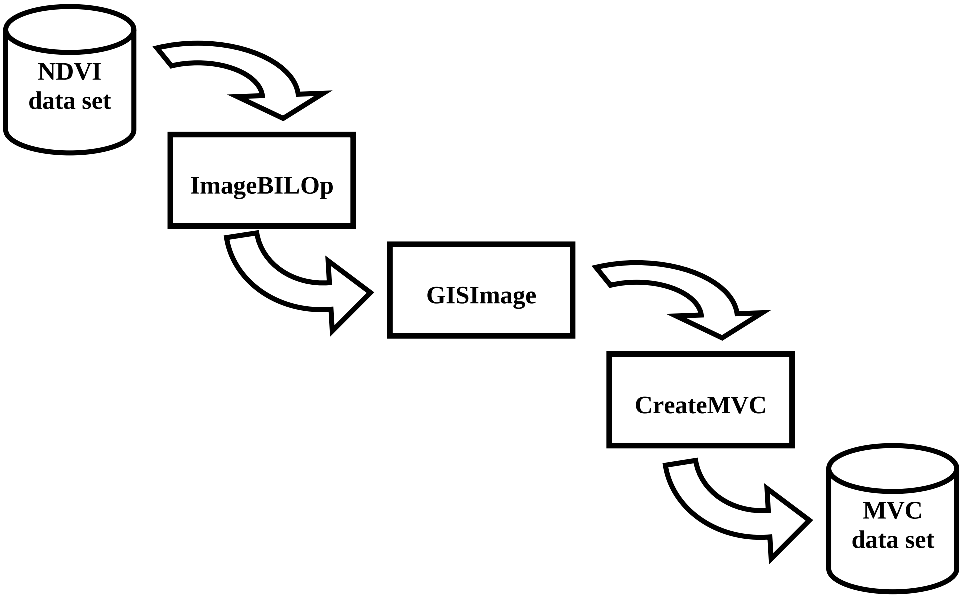


Figure 5.15: Creation of the dataset of MVC images

Figure 5.16 describes the creation of the three different dataset of images of risk derived by the MVC dataset.

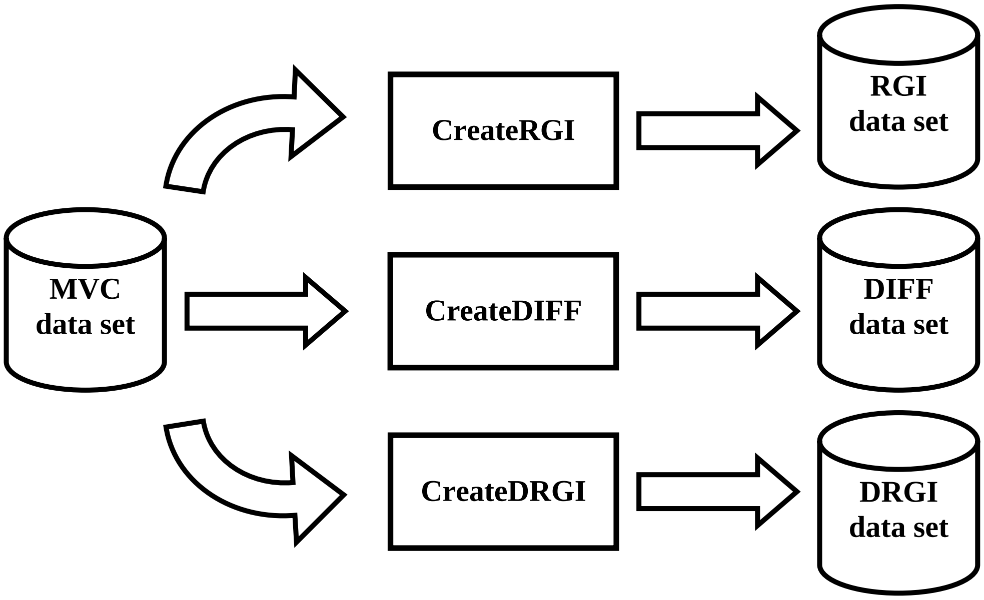


Figure 5.16: Creation of the datasets of images derived by the MVC images

Figure 5.17 describes the process of creation of FWI images derived by the original Microsoft Access database of FWI related information.

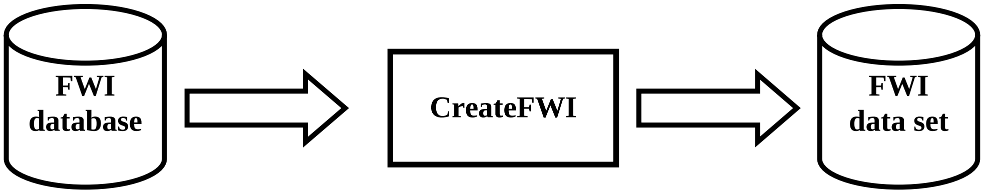


Figure 5.17: Creation of the dataset of FWI images

Figure 5.18 shows the three analyses applied to each index in order to obtain the final results

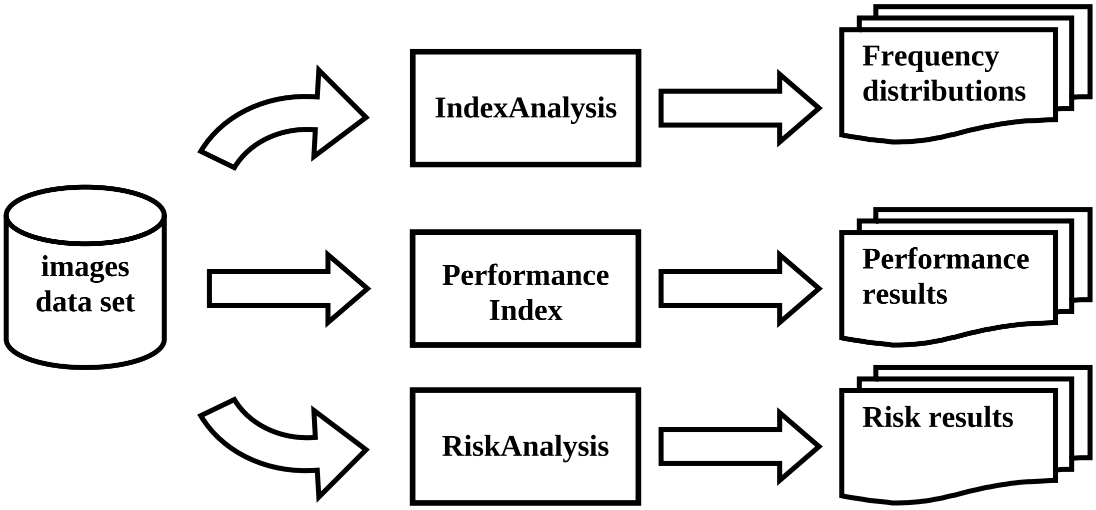


Figure 5.18: Three different analyses done over each considered index of risk

6 Results and Discussions

6.1 Qualitative approach

During the qualitative analysis two dataset of values were obtained for each index of risk. The first dataset referred to the observed values of risk during the entire time series. The second dataset referred only to the values of risk observed on communes having a fire in a considered day. The first dataset permitted to trace the frequency distribution of values of the indices during the years. The second dataset permitted to trace the frequency distribution of values of the indices over burnt communes. A visual comparison of the two distributions represents the analysis which has been called qualitative. The advantage of this approach results in the easy computation and analysis; the plotting of the distributions of frequency is not complex and the valuation of results almost immediate. It would verify the basis hypothesis that a fire tends to occur where a high level of risk is present. Thus, the distribution of values assumed during a fire should be shifted towards a higher level of risk respect than the normal distribution of values. If this was observed, a statistical difference between values over burnt areas and over areas in which fires did not occurred would be present. Hence, this difference would be the starting point to justify the use of the values of an index to estimate levels of risk.

During the analysis the dataset of values for the entire study period were divided by six different sets, each one containing data referred to only a particular month out of the six considered in the time series, from May to October. The aim of this division was to further investigate the behaviour of each index during the different months of the year in order to establish if a particular index could be better adopt in some month than others.

To better understand the procedure adopted by the qualitative approach in order to obtain the following results it is reported in detail the case of the MVC-NDVI analysis:

1) the DailyImages Java class reads each NDVI image and applies the vegetation mask and the crop procedure on it;
2) the CreateMVC Java class is applied to the daily NDVI images and a 10 days Maximum Value Composite image is created for each day of the study period;
3) the ImageJPEG Java class creates a JPEG image for each daily NDVI image. This permits to directly exclude bad quality images and to check the results of the composite procedure;
4) for each of the daily MVC images, the ComsValue Java class sets the pixels below a commune to an unique value that is the minimum observed value for that commune during that day. This permits to have only one value for each commune each day. Each time, the retained value corresponds to the value of maximum risk observed;
5) the IndexAnalysis Java Class is applied to the dataset of images obtained by the previous point. Each image is analysed and the number of time each NDVI value is observed is extracted for the entire study period. The observed values are grouped by zone and by month;

6) the RiskAnalysis Java Class is applied to the dataset of images obtained by point 4. For each day, the database of fire occurrences is queried and the NDVI values present below a commune with fire are extracted. The observed values are grouped by zone and by month;
7) the graphs reported on figure 6.1 and 6.2 are derived by the results obtained by points 5 and 6. The line represents the relative frequency distribution of NDVI values as observed by point 5. Meanwhile the distribution of NDVI values over burnt areas obtained by point 6 is represented by bars.

For the others indices, the procedure was the same. They differed only by the retained value by the ComsValue class. Depending on the index behaviour the retained value could be the maximum observed in the commune or the minimum.

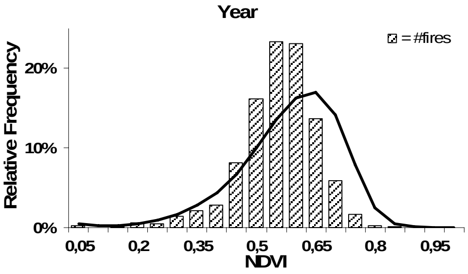
The following chapters report the results obtained grouped by index of risk. For each index, the results have been further divided by area of analysis, Zone 1 or Zone 2, and by different months, as explained before. In order to better present the results, it was decided to present the different distributions of frequency as relative frequency distribution; which permitted to quickly compare distributions of different indices. The distribution of values over burnt communes is represented by a bar graph of the number of fires grouped by the values of the index of risk. Depending on the index of risk considered the bar graph should be shifted towards left, if lower values of the index are referred to higher level of risk, or towards right, if higher values of the index are referred to higher level of risk.

6.1.1 MVC-NDVI results

The analysis of the MVC-NDVI data would investigate the possibility to directly adopt this kind of information in the context of forest fire risk estimation. The analysis highlighted a more evident difference between distributions in Zone1 (figure 6.1) than in Zone2 (figure 6.2). In this second area results tend to be worse jointly with the summer period. In this period, it is possible to observe that the two distributions tend to have similar maximum; which could be considered as the value more probable to have during the particular study period. Thus, if the two distributions had similar maximum, it would mean that a fire could occur assuming a value which is one the more probable. This similitude is observable for almost any month of the year in Zone2. Zone1, less subjected to vegetation stress during the summer period, presents generally better results. Even though, similar behaviour of the distributions is still possible to observe in the graph relative to the month of August.

6.1.2 DIFF results

The DIFF index is based on the relative decrement of NDVI values over a particular area. In this index the concept of risk is linked to that decrement; more the observed decrement, more the risk. This index would solve the problem of the generic range of values adopted by using the NDVI information directly. In the previous index, in fact, the level of risk was linked to low NVDI values; even though different areas may present a really different range in the observed NDVI values. Because of the DIFF nature, in this case a high value of DIFF is linked to a high level of risk. Thus, the expected shift between frequency distributions of values and fire distributions should be toward right. Difference between distributions is observable for both the zones (figure 6.3 and 6.4). It is noticeable the worst results during the first months of the retained period, which is consequence of the index structure. The index is made by the difference between the maximum observed value since the begging of the season and the daily value. Thus, during the first period of time, the index needs to be initialised and, as a consequence, it presents a low level of risk.



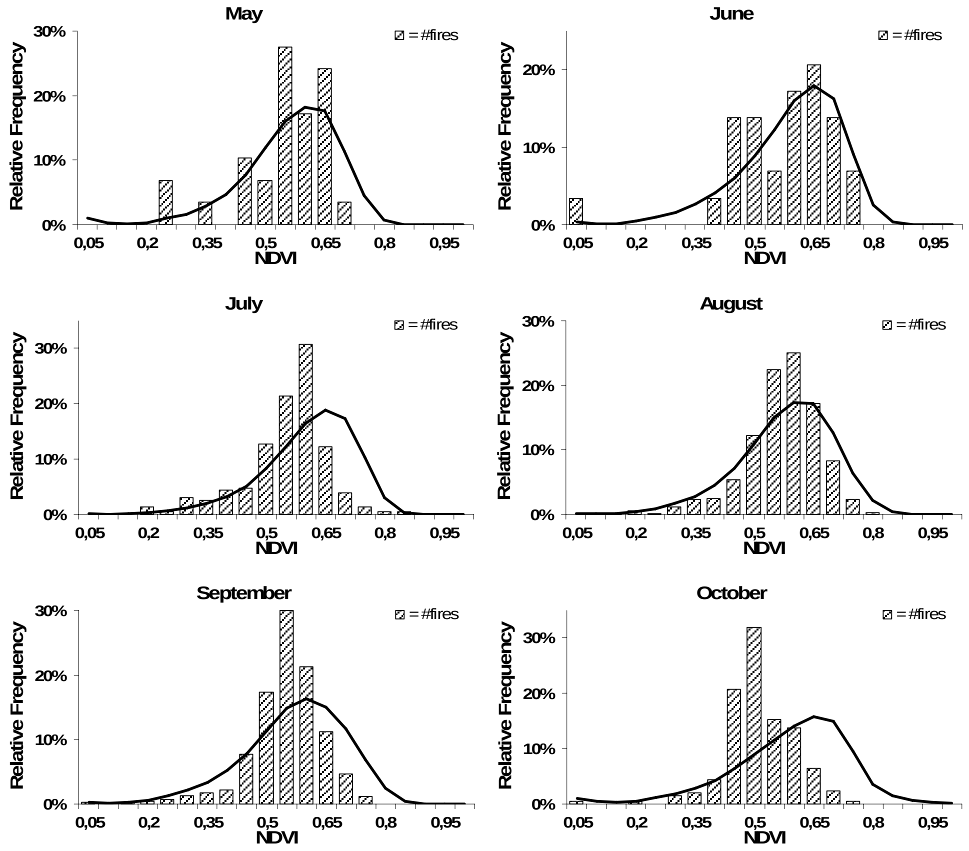
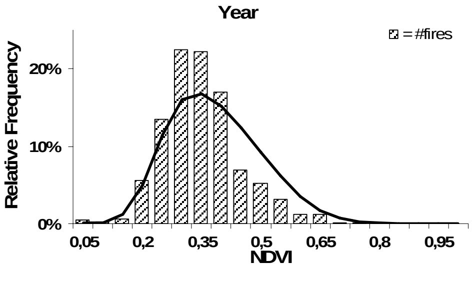


Figure 6.1: Relative frequency distributions of MVC-NDVI values considering the complete time series (year) or considering one month at time and bar diagrams of the number of fires occurred by MVC-NDVI value for Zone 1.



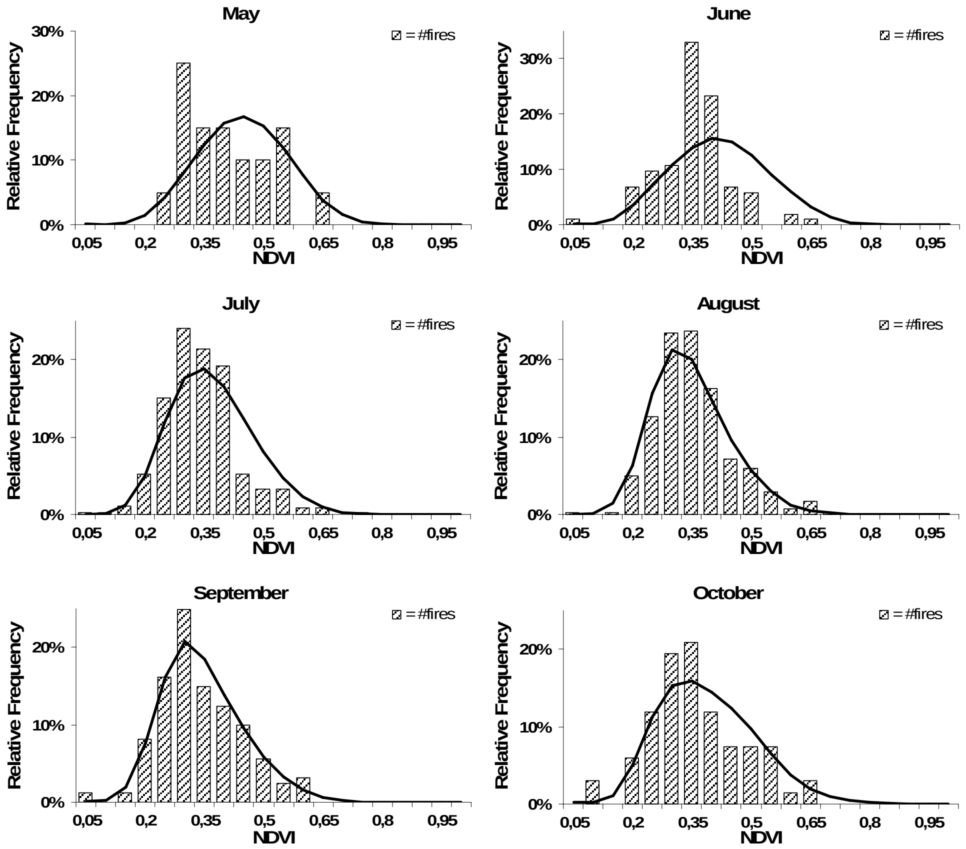
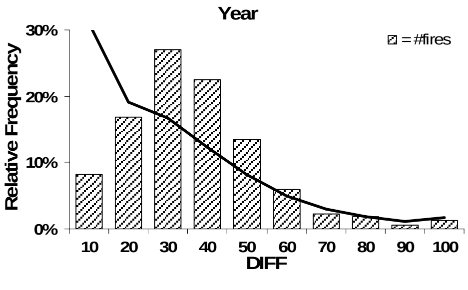


Figure 6.2: Relative frequency distributions of MVC-NDVI values considering the complete time series (year) or considering one month at time and bar diagrams of the number of fires occurred by MVC-NDVI value for Zone 2.



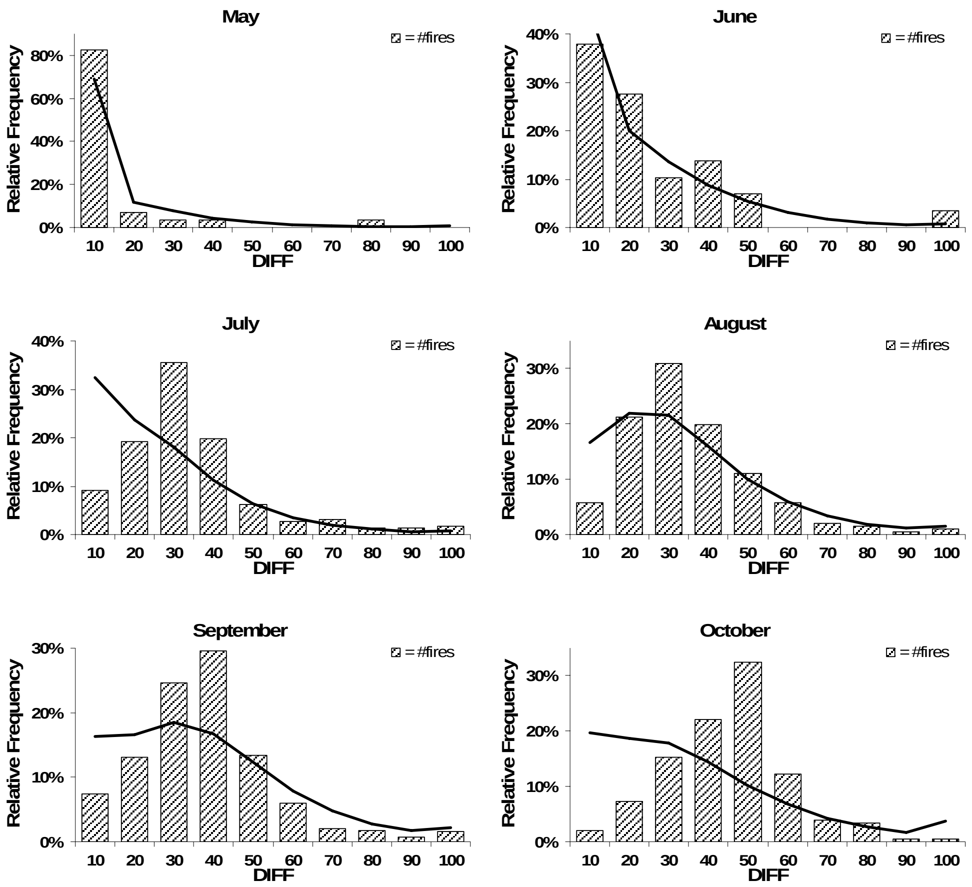
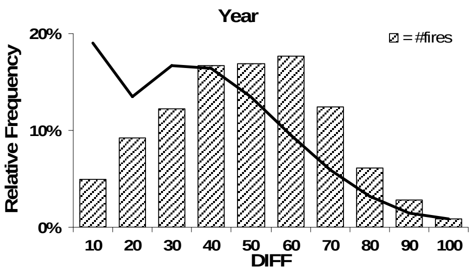


Figure 6.3: Relative frequency distributions of DIFF values considering the complete time series (year) or considering one month at time and bar diagrams of the number of fires occurred by DIFF value for Zone 1.



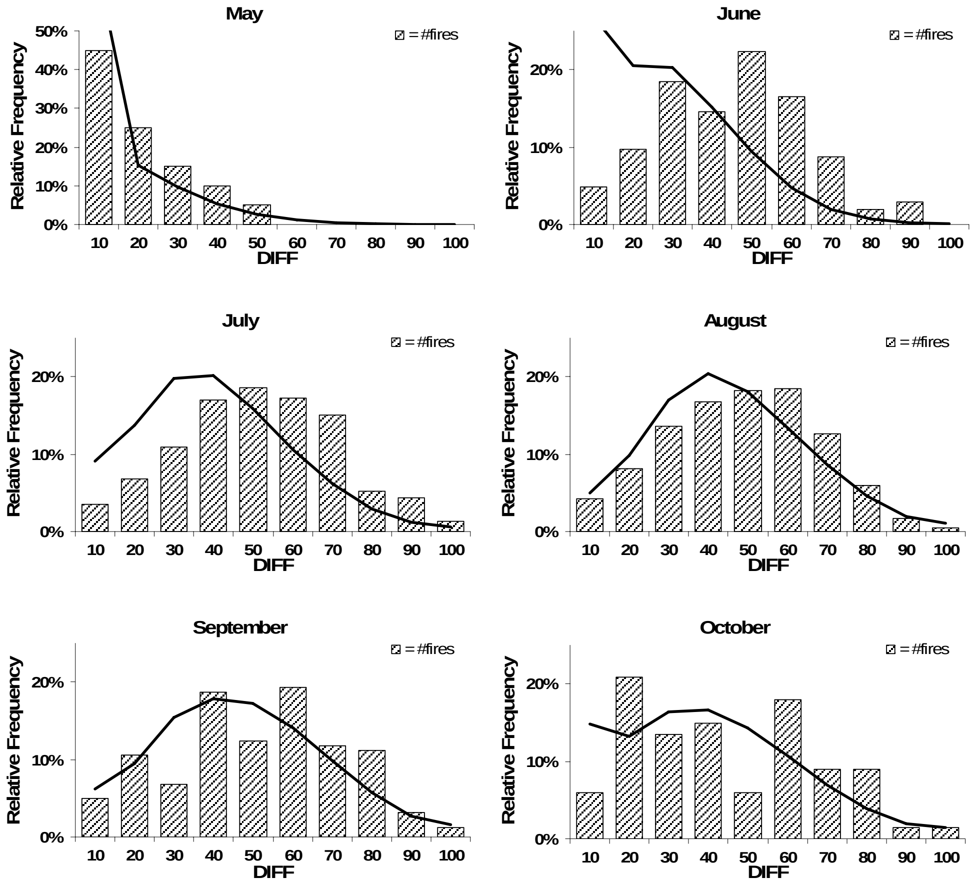
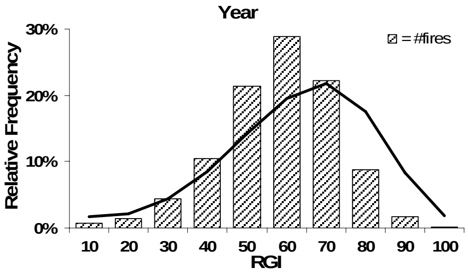


Figure 6.4: Relative frequency distributions of DIFF values considering the complete time series (year) or considering one month at time and bar diagrams of the number of fires occurred by DIFF value for Zone 2.

6.1.3 RGI results

The RGI index further extends the concept of local risk evaluation. The concept of risk when NVDI is directly used regards the link between high risk and low values. Nevertheless, it has been discussed about the difficulties to use a general definition of low value. The DIFF index partially solved this problem considering each area differently from other. However, also in that case the idea of NDVI decrement could be considered too general. In fact, the definition of high decrement could be dependent from place to place. It is possible to observe higher decrements in certain areas than in others; even though they could be subjected to similar level of risk. Different climate conditions and vegetation situation could result in really different NDVI behaviours. Consequently, the analysis of NDVI indices was extended with the introduction of the RGI index. This index, in fact, permits to evaluate the risk of fire in a more strictly local concept. The estimation of low NDVI values, and consequently high levels of risk, is done by considering the range of values assumed by a particular area. Thus, it necessitates of the minimum and the maximum NDVI value observed over a particular area during the considered time series. This necessity could be considered as a disadvantage in the adoption of this index, because it requires knowing a priori the maximum and minimum values. Nevertheless, the presence of a time series of data of ten years permitted to consider the finding maximum and minimum values as boundaries for the admissible values for a place. The RGI range of values is from 0 to 100, where 0 stands for the highest possible level of risk. Thus, the distribution regarding values over burnt areas should be shifted toward left comparing to the normal distribution of values. Also for this index the observable difference between distributions is not so remarkable (figure 6.5 and 6.6). It is possible to note how, also for RGI, the distributions tend to have the maximums placed in the same region of values. Results are really variables from month to month with worst condition in August for Zone2. In this month, it is possible to note a shift of the distribution of fires toward right instead than left. This means that most of the fires tend to happen assuming a value of risk lower than the average.



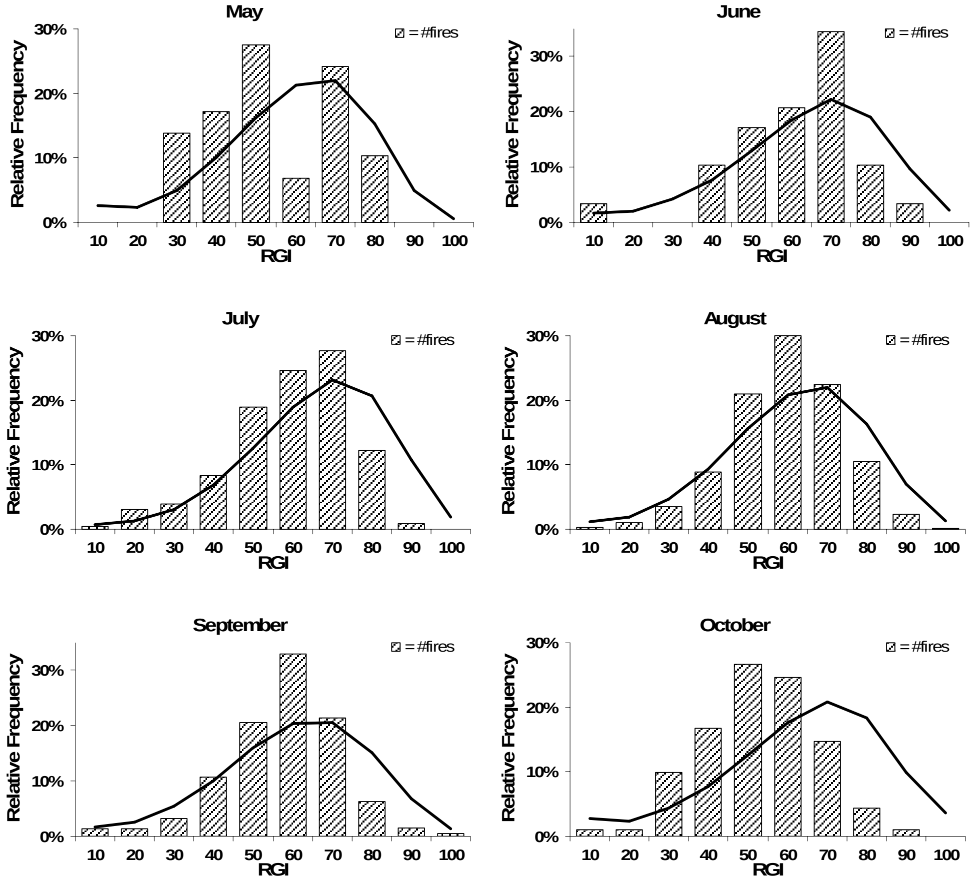
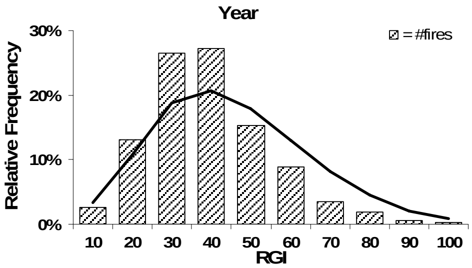


Figure 6.5: Relative frequency distributions of RGI values considering the complete time series (year) or considering one month at time and bar diagrams of the number of fires occurred by RGI value for Zone 1.



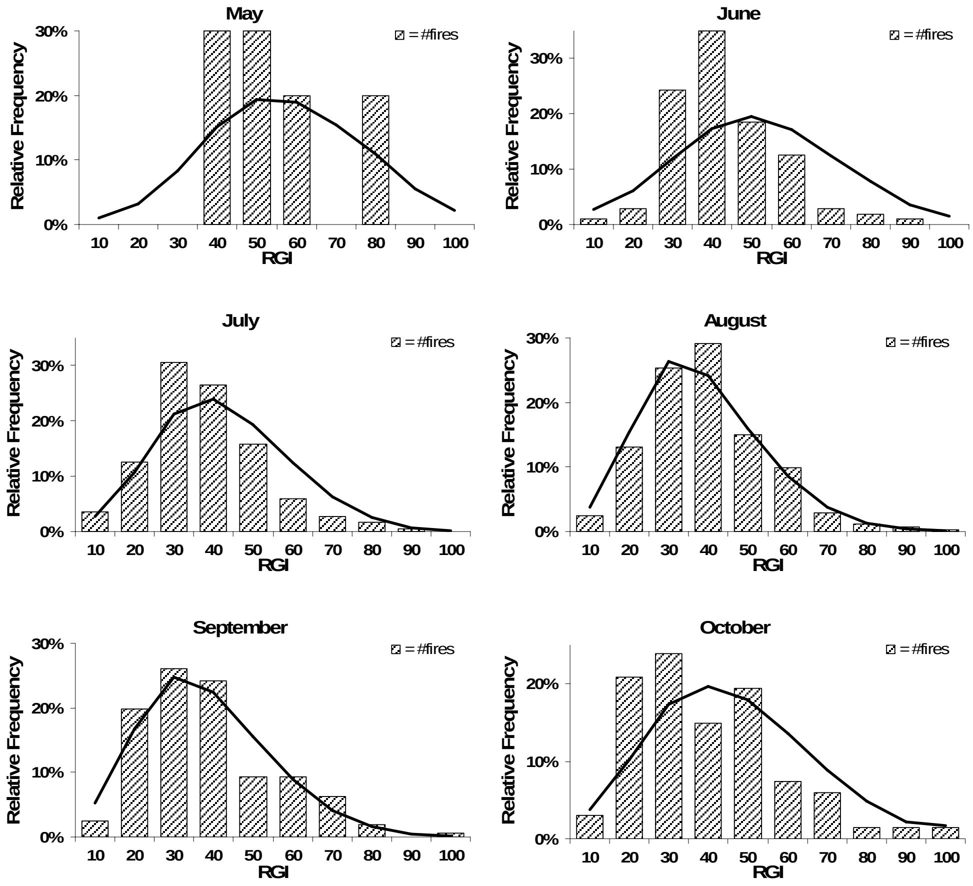


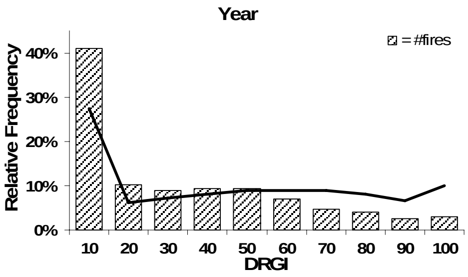
Figure 6.6: Relative frequency distributions of RGI values considering the complete time series (year) or considering one month at time and bar diagrams of the number of fires occurred by RGI value for Zone 2.

6.1.4 DRGI results

The last considered index for analysis based on the NDVI was the DRGI. This index is a new index developed in the context of the present study. It would evaluate the condition of risk considering the inter-annual variability of values instead of the intra-annual. The index derived by the RGI methodology where, instead of considering a global minimum and maximum value for an area, it was consider the minimum and the maximum value an area assumed during a particular day for each of the considered year. Thus, the DRGI considered daily maximum and a minimum values. As for RGI, the range of possible values is from 0 to 100, where 0 is representative of the maximum level of risk observable. The results highlighted how the highest percentage of fires every month tends to occur assuming the lower class of risk (figure 6.7 and 6.8). Only the month of June for Zone2 presented a different behaviour. However, also in this case, even if less evident, the distribution of burnt values tends to be similar to the global one.

6.1.5 FWI results

The FWI index is the only index adopted in the present study not to be derived by remote sensing. The aim was to compare the results obtained by remote sensing with results obtained by meteorological parameters. The FWI could assume values from 0 to more than 100; higher the value, higher the level of risk. Results showed the tendency for FWI to present higher values over burnt areas (figure 6.9 and 6.10). Only during July and August in Zone2, FWI presented behaviour similar to NDVI-derived indices where both distributions assumed similar maximum. In the global analysis, like for most of the monthly analysis, the difference between the distributions is more evident and clear than in the case of NDVI-derived indices. Also for summer periods, FWI continues to present clear distinctions between distributions.



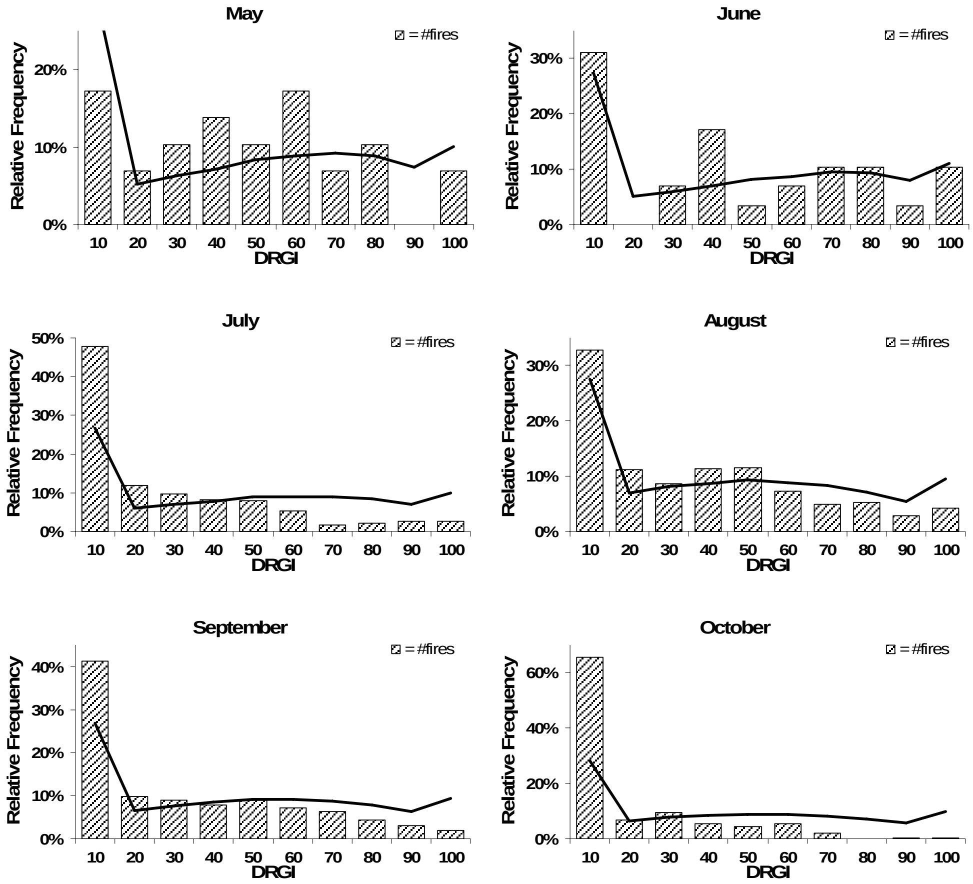
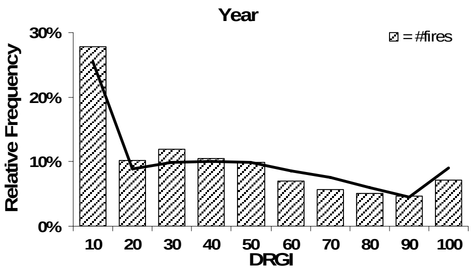


Figure 6.7: Relative frequency distributions of DRGI values considering the complete time series (year) or considering one month at time and bar diagrams of the number of fires occurred by DRGI value for Zone 1.



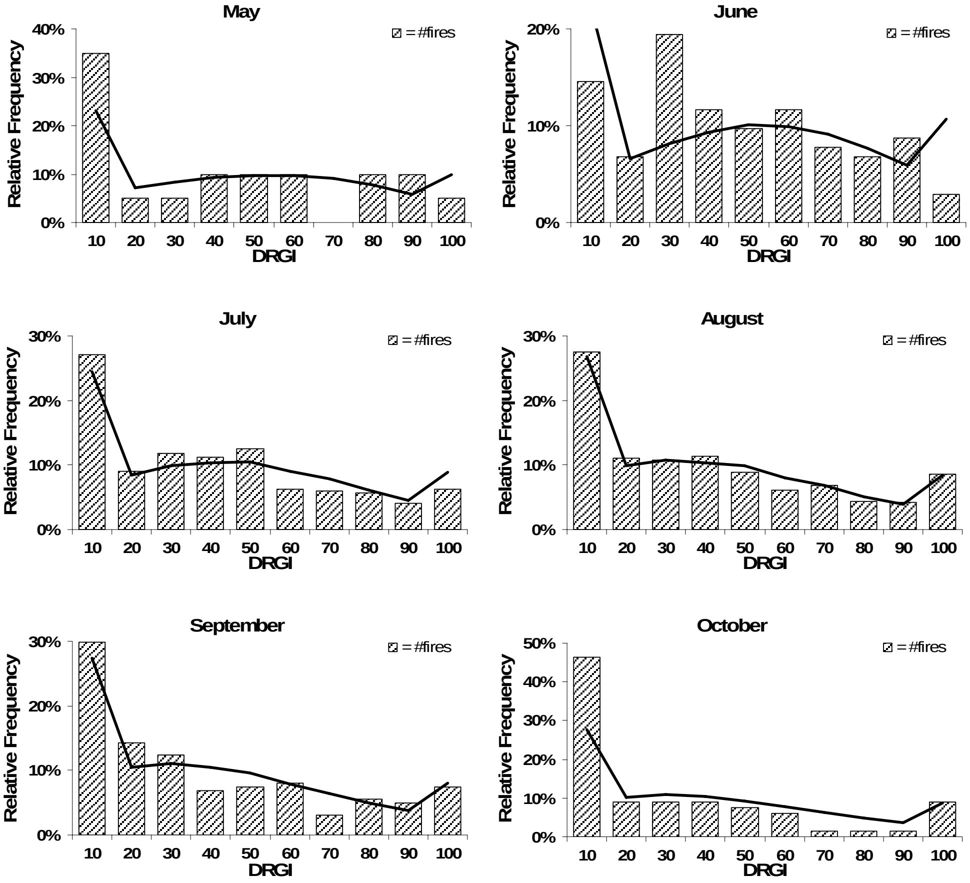
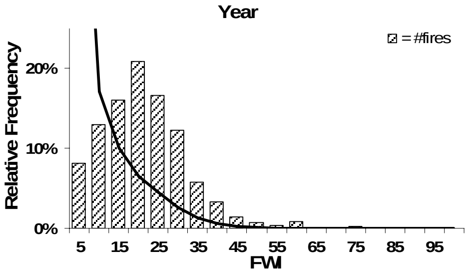


Figure 6.8: Relative frequency distributions of DRGI values considering the complete time series (year) or considering one month at time and bar diagrams of the number of fires occurred by DRGI value for Zone 2.



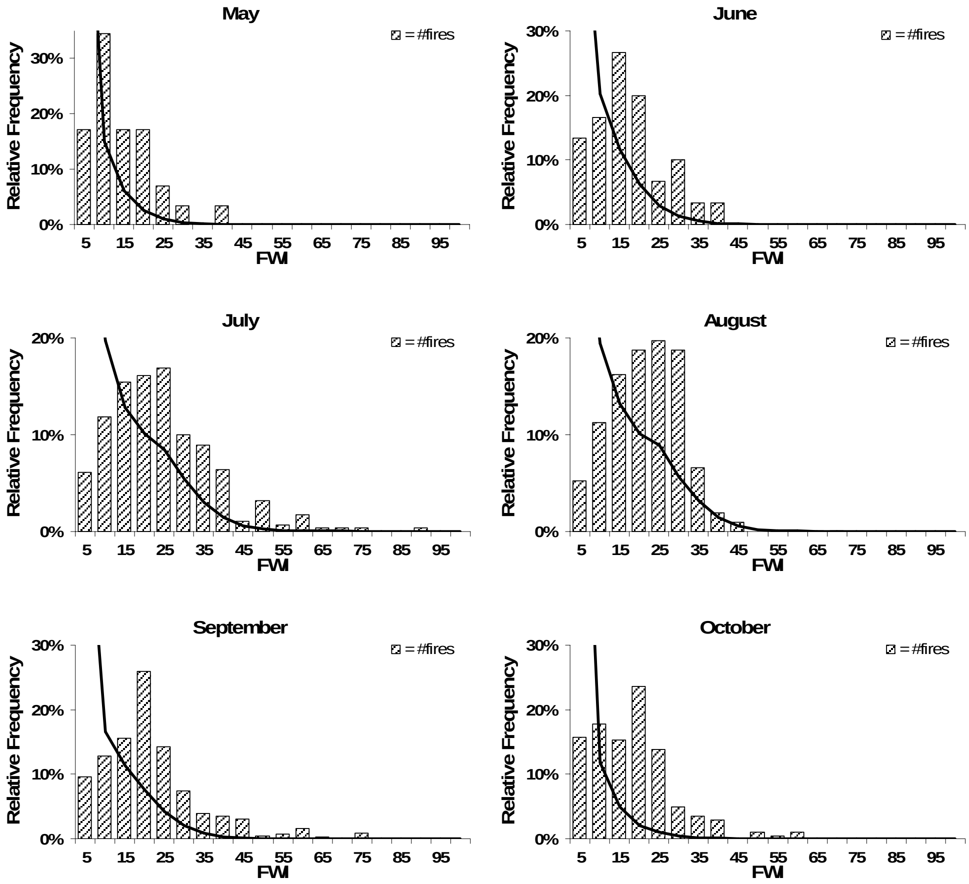
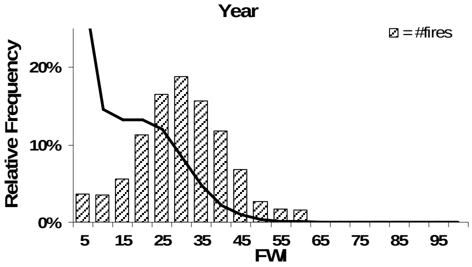


Figure 6.9: Relative frequency distributions of FWI values considering the complete time series (year) or considering one month at time and bar diagrams of the number of fires occurred by FWI value for Zone 1.



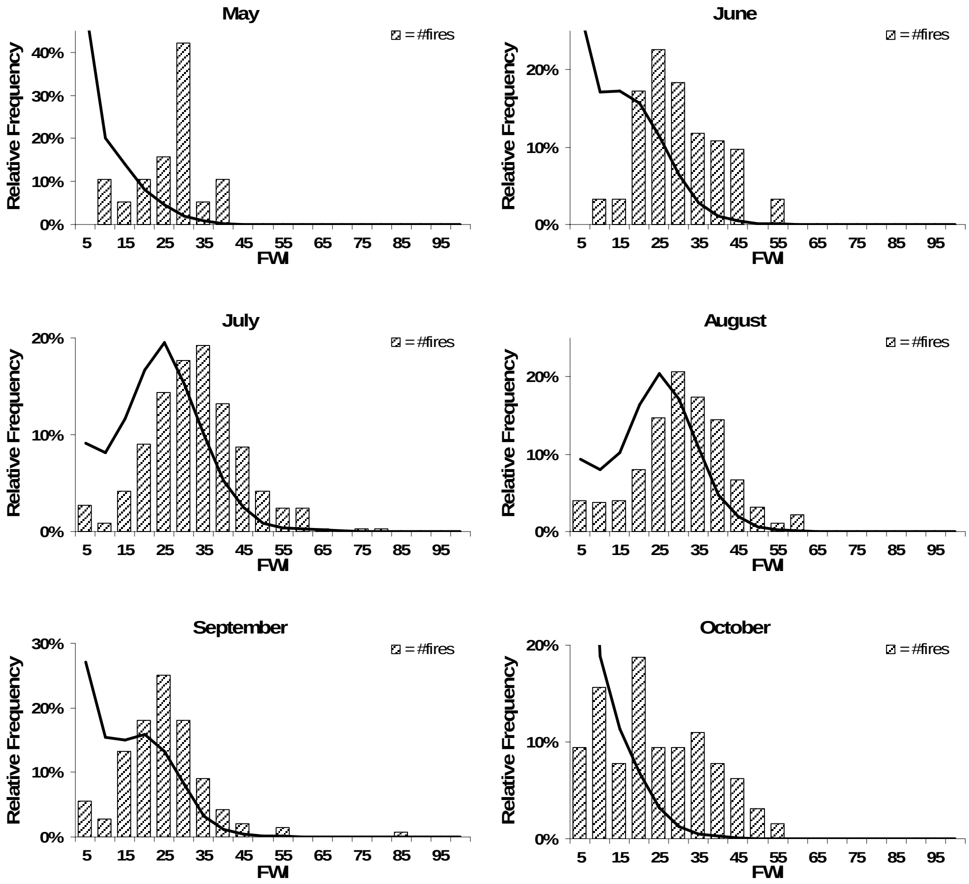


Figure 6.10: Relative frequency distributions of FWI values considering the complete time series (year) or considering one month at time and bar diagrams of the number of fires occurred by FWI value for Zone 2.

6.1.6 Comparison

The qualitative approach would evaluate differences between the distributions of value over burnt areas and the normal distribution of values. It investigated if burnt areas assumed higher levels of risk than others. More the difference between distributions is evident more the distribution were considered statistically different. Hence, a particular index is more suitable to be use as an index of risk. The better potential of the FWI index has been highlighted both globally than month by month. Nevertheless, the qualitative analysis presents some limits. First of all, it does not permit to effectively compare results coming from different indices. Second, the obtained results are relative to a frequency distribution computed all over the years or month by month. Thus, a comparison between values was not performed day by day. A particular index could present a high percentage of fires occurred assuming higher values of risk but, at the same time, it could be not able to discriminate burnt areas from others. Thus, due to the nature of this analysis, the presence of different distributions of values is a necessary requirement but not a sufficient one. This graphical analysis does not permit to evaluate the entity of the difference between distributions. Thus, the statistical analysis wants to solve this problem.

6.2 Statistical results

The previous chapter presented the results obtained by the qualitative analysis. However, even that analysis presented good potential in an exploratory analysis, it does not provide a method in order to evaluate and compare numerically the obtained results. The statistical analysis introduced by this work would solve this problem. This analysis was based on the use of the performance index, as describe in chapter 5.7. The performance index evaluates the effective potential of an index of risk by comparing values over restricted areas to all the others values. This estimates how much the information derived by the use of a particular index of risk introduces added value than the use of pure random values. As described in chapter 5.7 the performance index was introduced by Mandallaz in order to better estimate the characteristics of a specific index. The introduction of the use of the random value in order to estimate the performance of an index permitted the detachment of the obtained result from the index characteristics, as the range of values or the scale of reclassification. Thus, it permits an easy comparison of the results obtained by different indices.

As for the qualitative analysis, to better understand the procedure adopted by the statistical approach, the case of the MVC-NDVI analysis is reported in detail. This approach utilises the same images produced by the previous approach (Chap. 6.1), thus the points 1 to 4 are the same:

5) the PerformanceIndex Java class queries the fire occurrence database daily. If a fire is present for a particular day, the performance index, the maximum performance index and the random performance index for that day are computed;
6) Figure 6.11 and 6.12 are obtained by summing up the number of time the performance index is bigger than the random performance index (white bar) and the time it was lower (black bar);
7) Figure 6.12 is obtained by averaging the ratio performance indices.

The procedure is equivalent for each considered index.

Following are reported the results obtained by the application of the performance index to each index of risk analysed. For each zone of analysis, the number of days the considered index of risk presented better results than the use of randomness was reported. The results are reported both on a yearly base than on a monthly base. As described in the qualitative analysis, the division of the obtained results in a monthly base permitted to evaluate the behaviour of the index in function of the period and, thus, to evaluate if an index is better suitable for certain periods of time than others. Afterwards, it was reported the results obtained by the performance index ratio. This last analysis assessed in a scale from 0 to 1 the goodness of the obtained results, where 1 represented the ideal case in which all the observed forest fires occurred assuming the maximum observed level of risk. The last chapter regrouped the obtained results by each index in only one graph and compares them.

6.2.1 MVC-NDVI performances

The application of the performance index over values belonging to MVC-NDVI images showed that, considering the entire time series, the index of risk performed better than randomness in the 72% of the days in Zone1 and in the 60% in Zone2. However, the same analysis, conducted considering one month a time, highlighted an interesting result especially for the Mediterranean region (Zone2). The previous percentage of values dropped to the 49% of the cases in August demonstrating that the MVC-NDVI presents the worst performances during the worst period for forest fires (figure 6.11). Also the analysis of the performance ratio index follows the conclusions of the performance index showing the drop of the MVC-NDVI potential just during the period of major fire occurrences (figure 6.12). Even so the results obtained by the use of the performance ratio index will assume more relevance in the comparative analysis of results.

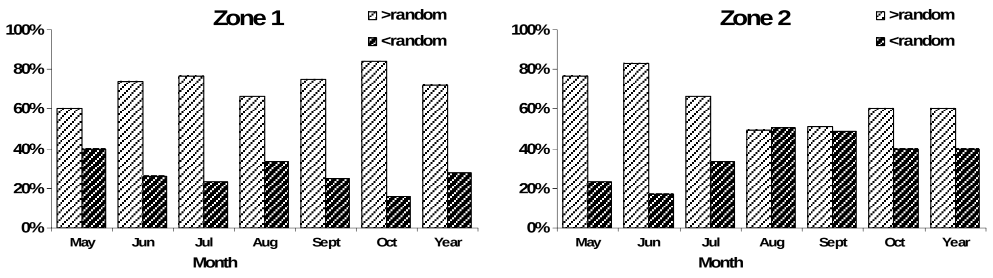


Figure 6.11: Relative number of days the value of the performance index was bigger, or lower, than the corresponding random value. Result concerns the analysis by month and the analysis for the entire time series (Year)

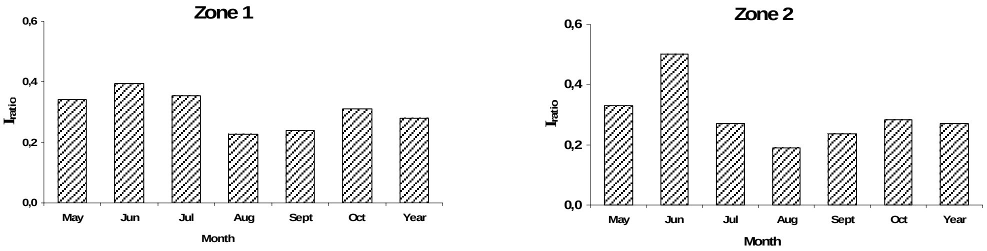


Figure 6.12: Monthly and year average value of the ratio performance index obtained by the MVC-NDVI.

6.2.2 DIFF performances

The study of the DIFF index produced an overall result where the index performed better than randomness in the 67% of the days in zone 1 and in the 65% in Zone2 (figure 6.13). Since the DIFF index was based on the decrement of NDVI values starting from the beginning of the fire season, it presented worst performances in the month of May; which contributed to decrease the global performances. Nevertheless, especially for the Zone2 the decrement in the performance was less visible than for the direct use of MVC-NDVI. The DIFF index presented a monthly performance better than randomness in most of the observations; assuming a steadily percentage of about 60%. The analysis of the performance ratio index demonstrated that also for the DIFF index lowest performances were observed during the month of August (figure 6.14).

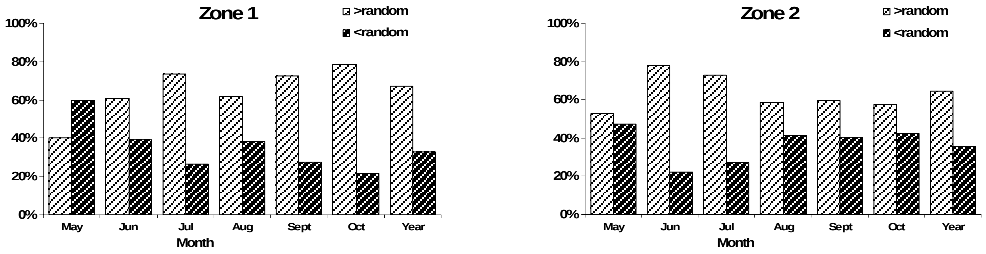


Figure 6.13: Relative number of days the value of the performance index was bigger, or lower, than the corresponding random value. Result concerns the analysis by month and the analysis for the entire time series (Year)

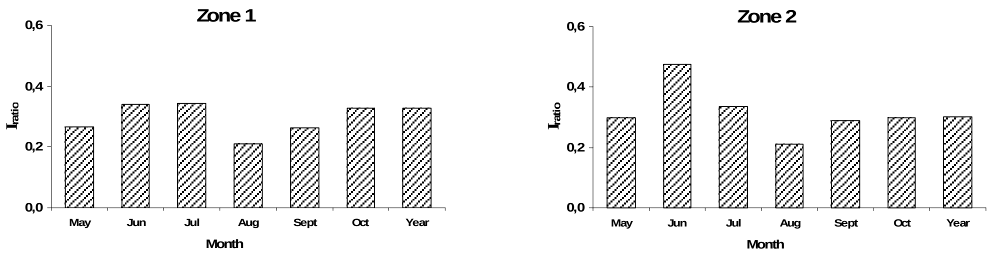


Figure 6.14: Monthly and year average value of the ratio performance index obtained by the DIFF.

6.2.3 RGI performances

The performance index analysis applied to the RGI showed that the index performed better than randomness in the 72% of the days in Zone1 and in the 58% in Zone2. Even though the better results obtained by this index in the Zone1, the analysis by month highlighted the bad performance in the Mediterranean area (Zone2) where the percentage of time RGI worked better than random dropped to the 48% of the cases in August and 47% in September (figure 6.15). This implies that in about one case out of two using information coming from the RGI did not provide better results than using randomness. The analysis of the performance ratio index follows the conclusions of the performance index showing the drop of the RGI potential during the period of major fire occurrences (figure 6.16). It was highlighted also the bad discriminatory potential of the index in the month of May in Zone2.

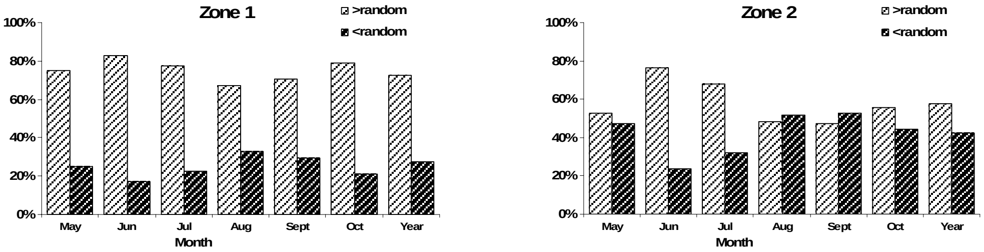


Figure 6.15: Relative number of days the value of the performance index was bigger, or lower, than the corresponding random value. Result concerns the analysis by month and the analysis for the entire time series (Year)

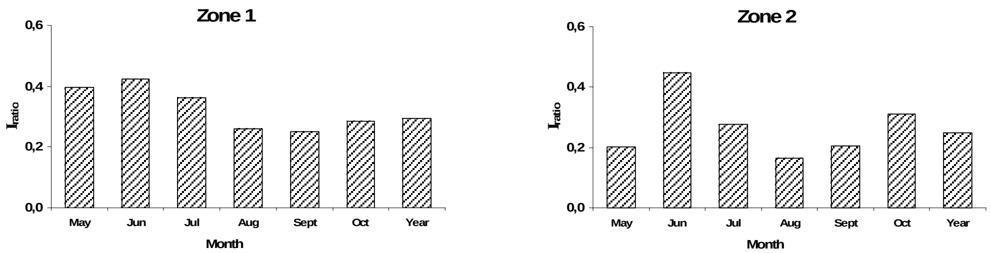


Figure 6.16: Monthly and year average value of the ratio performance index obtained by the RGI.

6.2.4 DRGI performances

Even though the DRGI was based on the same methodology than RGI, the obtained results by the analysis with the performance index highlighted the better potential of this last index. The global result is almost equivalent, the DRGI performed better than randomness in the 72% of the days in Zone1 and in the 57% in Zone2. Nevertheless, the analysis by month highlighted a general trend during the year better than RGI for both the zones (figure 6.17). Even so, also for the DRGI, the performances tend to decrease during the months arriving to furnish no added value in the month of September. The analysis of the performance ratio index followed the same conclusions (figure 6.18).

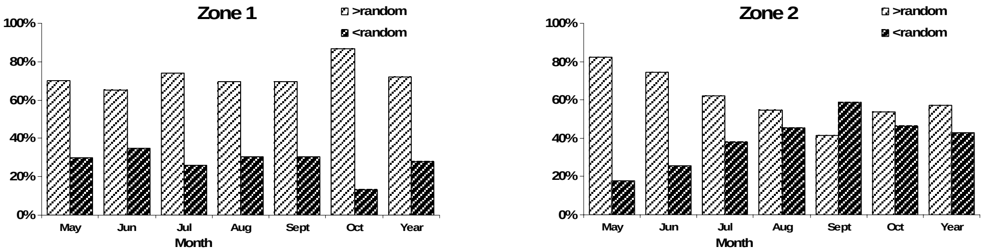


Figure 6.17: Relative number of days the value of the performance index was bigger, or lower, than the corresponding random value. Result concerns the analysis by month and the analysis for the entire time series (Year)

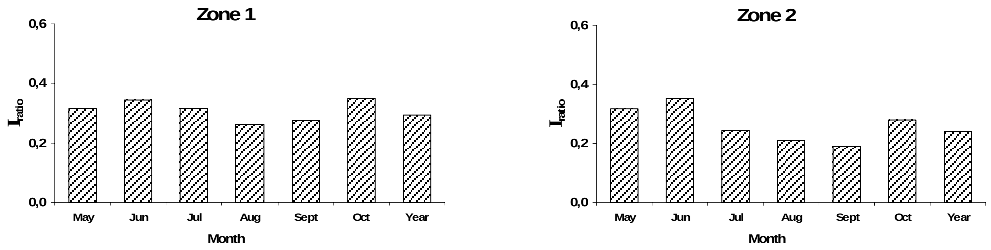


Figure 6.18: Monthly and year average value of the ratio performance index obtained by the DRGI.

6.2.5 FWI performances

Following the conclusions obtained by the qualitative analysis, the FWI produced the best results also in this statistical analysis. The performance index showed that FWI worked better than using randomness for the 83% of the observations in the Zone1 and for the 82% in Zone2, showing a really good performances all over the months (figure 6.19). The average value of the performance ratio index was 0.42 for Zone1 and 0.47 for Zone2; values that will assume more meaning during the following comparison with the performances obtained by the use of NDVI (figure 6.20).

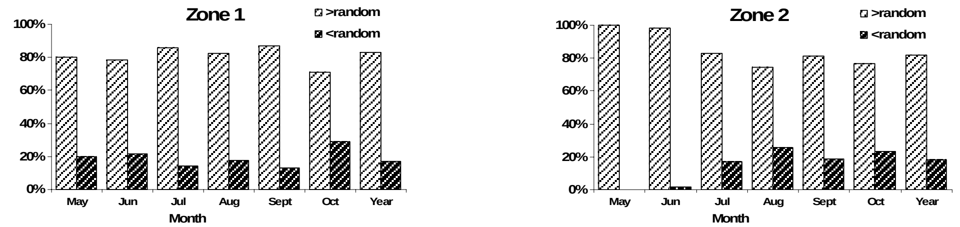


Figure 6.19: Relative number of days the value of the performance index was bigger, or lower, than the corresponding random value. Result concerns the analysis by month and the analysis for the entire time series (Year)

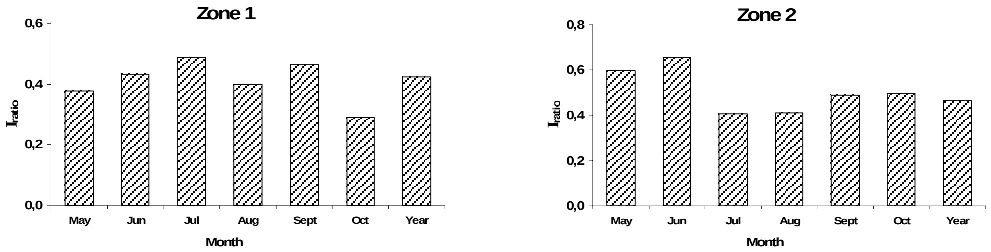


Figure 6.20: Monthly and year average value of the ratio performance index obtained by the FWI.

6.2.6 Comparison

A comparison only of the results obtained by indices NDVI-derived has been carried out before the comparison with results obtained by FWI because of the generally better results obtained by this last one. As showed by figure 6.21, for Zone1 all the indices produced results greater than 60%. Globally the indices worked better than randomness in the 72% of the days with fire. Only the DIFF index produces inferior results because of its bad performance during the beginning of the fire season. Also for

Zone2 results tend to assume similar behaviour among the indices. The global performance was about 60% for each index; results worse than Zone1. It is visible a steady decrement in performance during the months with minimum centred in August. However, even so some differences were visible, all the indices present a performance trend quite similar due to the fact they are all derived by the same source of information, the NDVI.

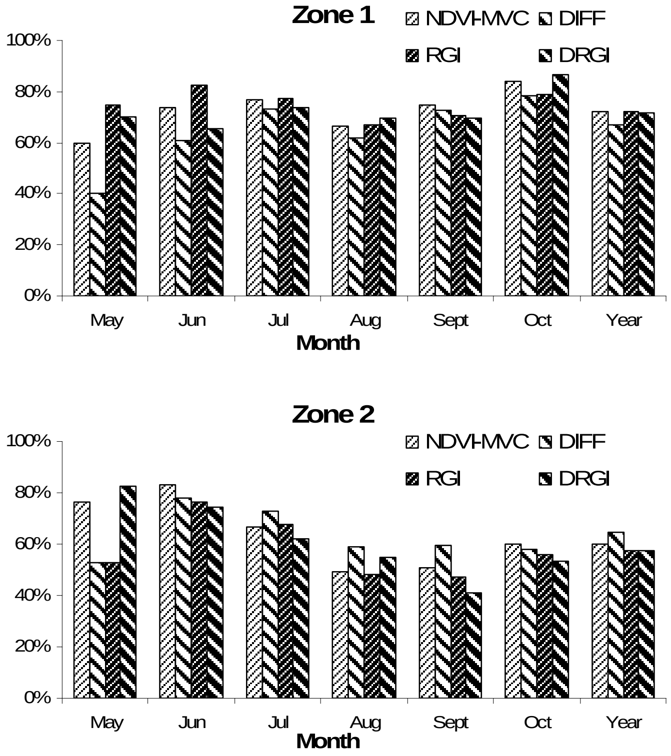


Figure 6.21: Relative number of days the value of the performance index was bigger than the corresponding random value considering indices of risk derived by NDVI. Result concerns the analysis by month and the analysis for the entire time series (Year).

Interesting conclusions are obtainable by the comparison of the results obtained by the NDVI-derived indices with the results obtained by the FWI (figure 6.22). In the context of the performance index analysis, the FWI produced an overall result better than all the others indices. In Zone1 it worked better than the random for the 83% of the observed cases, against the 72% obtained by the RGI. Also the analysis by month highlighted better results, especially during the summer period in which it worked better than NDVI in about the 12% more of the cases. Moreover, in Zone2 the FWI presented results still better. Globally, it worked better than random in the 82% of the cases, meanwhile only the DIFF index was able to reach the 64% of the cases. Good results were visible for each month. In particular, for the months of May and June the performances reached a value of about 100%. Really significant if compared to the 52% reach by RGI and DIFF.

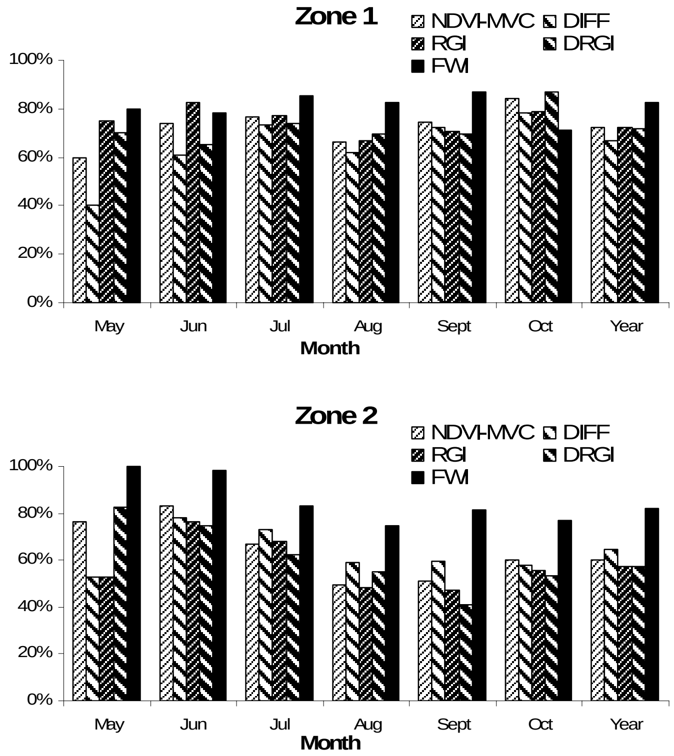


Figure 6.22: Relative number of days the value of the performance index was bigger than the corresponding random value considering indices of risk derived by NDVI and the FWI. Result concerns the analysis by month and the analysis for the entire time series (Year).

The performance index estimated the number of time the use of a particular index of risk produced added information than the use of randomness. However, a further analysis regarding the goodness of the indices was carried out. The introduction of the ratio performance index, in fact, permitted to evaluate not only when an index worked better than randomness but also how much better it worked. The optimistic case is represented by the value 1 of the ratio performance index, which means that all the fires occurred assuming the maximum level of risk observable for a particular day (see the examples in chapter 5.7). Thus, a better comparison of the performance is made possible by the introduction of the ratio performance index. Likewise for the performance index, it was possible to observe a global similar trend for the indices derived by NDVI. The index presenting better results was the DIFF both for Zone1 and Zone2, even though this conclusion is discussible if only one month at time is considered; different the month and the zone, different the index with best performance. Anyhow, the performances obtained by using indices of risk derived by NDVI values were poor considering that the average value of the ratio index observed was 0.32 and the maximum 0.49. The worst results were obtained by the RGI which presented a value of the ratio index equals to 0.16 in August. Moreover, also during this analysis it was showed up how indices derived from NDVI presents a drop in results during the period of major alert for forest fires (figure 6.23).

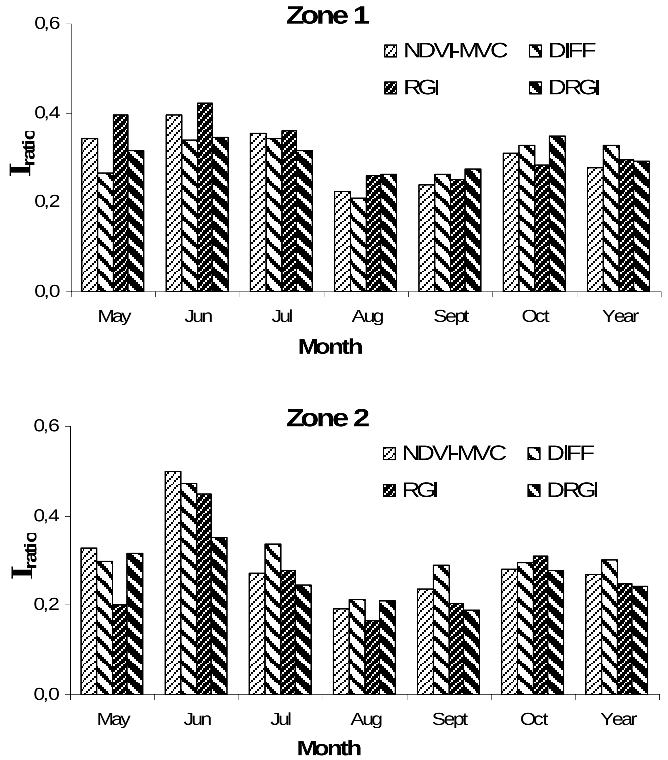


Figure 6.23: Monthly and year average value of the ratio performance index obtained by indices of risk derived by NDVI.

The comparison of the obtained results using the ratio performance index over NDVI indices and over FWI showed the better potential of the FWI index to be used as index for forest fire risk estimation (figure 6.24). FWI presented better results than all the NDVI-based indices in all the cases, exception done for May and October in Zone1. However, during these months the results were comparable to the ones obtained by NDVI. The overall result was 0.42 for Zone1 and 0.47 for Zone2. Quite different from the 0.32 and the 0.30 obtained by the DIFF in Zone1 and Zone2 respectively. Moreover, the FWI is less subjected to the performances decrement during the summer period.

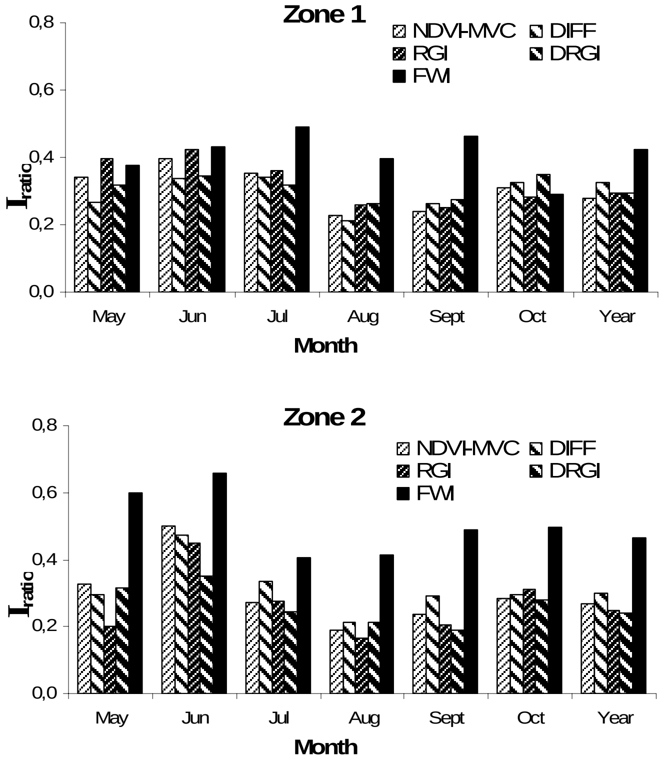


Figure 6.24 Monthly and year average value of the ratio performance index obtained by indices of risk derived by NDVI and the FWI.

7. Discussion and Conclusions

The primary objective of the present study is to investigate the potential of indices of risk as a tool for the detection of forest fire risk at country level and their possibility to be extended to a European level. This is carried out by a retrospective analysis of long term time series of remote sensing and meteorological data in Spain. The analysis is based on a qualitative and on a statistical approach. In both the approaches the distribution of the values of the indices over burnt areas is compared to the distribution of indices values all over the territory. If the proposed indices are successful, then a statistical difference between distributions should be observed. A more evident difference is indication of a better potential of a particular index of forest fire risk. The obtained results highlight a better capability of the meteorological index to be able to discriminate area of the territory more at risk than others. The indices derived by remote sensing data highlight a worse capability of discrimination. They presented the ability to detect period of particular stress for vegetation but not to discriminate a particular area at risk from surrounding areas.

The indices of risk, during the present study two different families of indices of forest fire risk have been investigated. Four indices of risk were derived by remote sensing data and one was derived by meteorological information; which descriptions were discussed deeply in previous chapters. Due to their low spatial resolution, these indices permit a wide coverage at high temporal resolution and, consequently, have been judged as better suitable to be applied for the creation of daily maps of forest fire risk at extended scale. Their different nature permits to assess the rule that the vegetation status or the meteorological conditions plays in the assessment of forest fire risk.

The assessment of the index potential, the different nature of the considered indices, however, leads to a non direct possibility of comparison of the indices. Superficial analyses of the results could easily conduct to good potential for an index. The analysis of the trend of observed values and the analysis of the distribution of fire in the territory, for example, furnish information which could be use to classify the potential of an index. Nevertheless, they are not able to deeply investigate the real potential of one index. Besides, the process of reclassification of index values into classes of risk could highlights a not real high level of correlation between number of fires and classes of risk. To better focus these problems, following are reported as example the results obtainable applying these analyses to the considered indices of risk.

Average trend, as described previously, the average trend would evaluate the potential of an index of forest fire risk by considering the trend of the assumed values during the year. This simple analysis investigates the presence of high level of risk during the period of major presence of forest fire events. The following graphs would reports the different behaviour of the different indices observed during the study period. They can not provide an indication of the real evolution of the values since only one value of a considered index in a considered day is reported. However, the general trend to assume values related to a higher level of risk during the summer period is noticeable.

In the case of MVC-NDVI, the trend of average values highlights the drop in values during summer for both the zones (figure 7.1). Even so, Zone 1 is characterised by a less visible difference in values between the average maximum and minimum. Nevertheless, it represents the North of Spain, area in which the lack of rainfall during the summer is less perceptible than in the Mediterranean region (Zone 2).

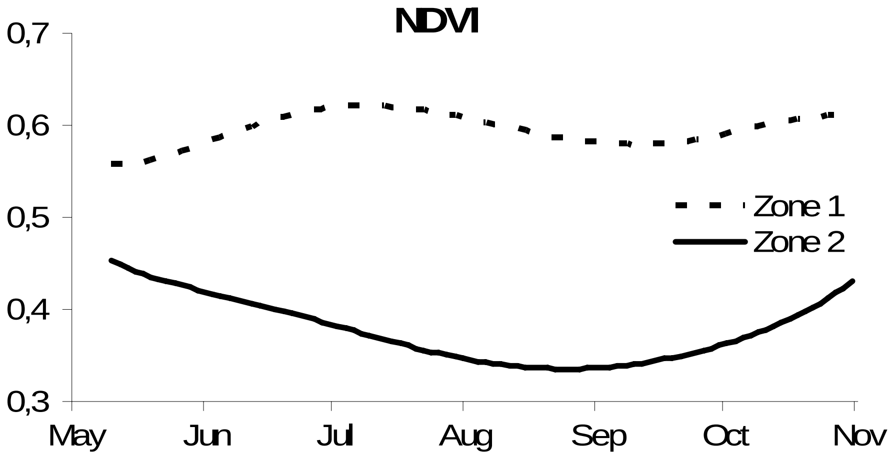


Figure 7.1: Average trend of NDVI values

The trend of DIFF values presents the highest levels of risk during the late summer (figure 7.2). Also in this analysis the curve relatives to Zone1 presents a different behaviour than the curve for Zone2. It is possible to observe a later begging of the season of risk for Zone1 than for Zone2 together with general lower levels of risk reached by Zone1.

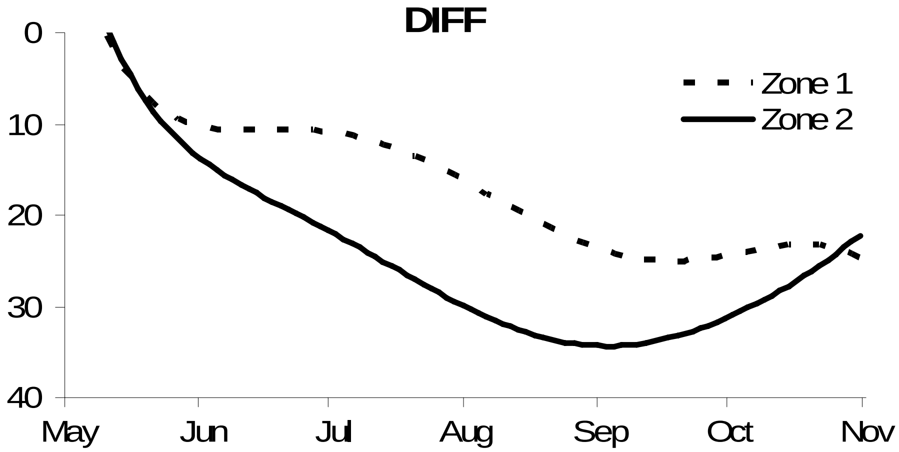


Figure 7.2: Average trend of DIFF values

The results obtained by the analysis of the average RGI behaviour highlight an interested outcome (figure 7.3). Meanwhile for Zone 2 the RGI values present the lowest values during the summer as expected, the behaviour for Zone 1 is completely different. In this area an almost steady trend of the average is noticeable. As a consequence, RGI should need a finer analysis in the northern region of Spain before to be used as an index of risk. Actually, the steady average value, consequence of a relatively close difference between the maximum and minimum value, may require an accurate calibration of the levels of risk.

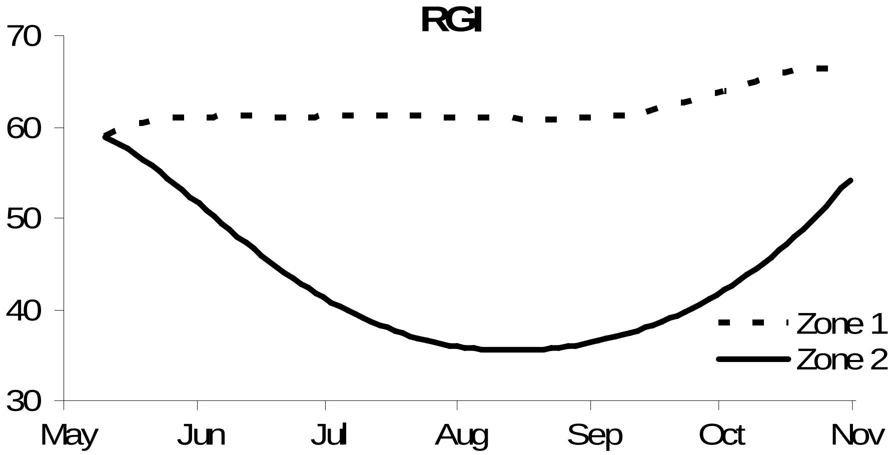


Figure 7.3: Average trend of RGI values

The trend of the average DRGI values presents behaviour quite similar for both the zones, except for the range of values (figure 7.4). Taking into account of a constant shift, it is possible to hypothesise the use of the similar levels of risk for both the zones; which could make easier a computation of an index of forest fire risk derived by DRGI.

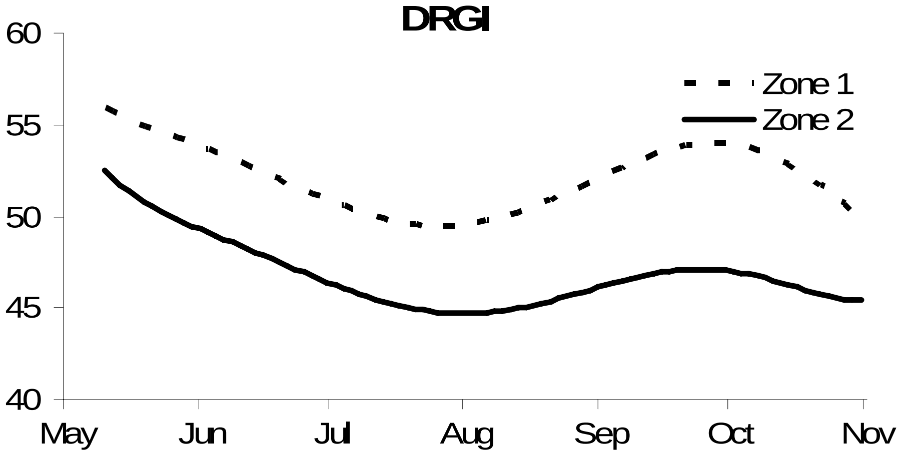


Figure 7.4: Average trend of DRGI values

The FWI index presented a clear average trend during the forest fire season period (figure 7.5). It was clearly noticeable the difference in the average values assumed at the beginning or at the end of the summer period and the ones assumed during the summer. The curves assumed a quite similar trend shifted of about a constant value all over the study period.

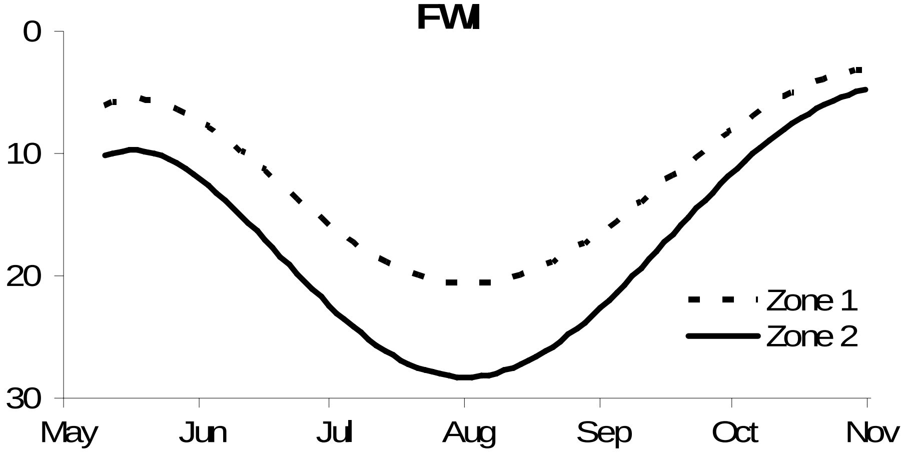
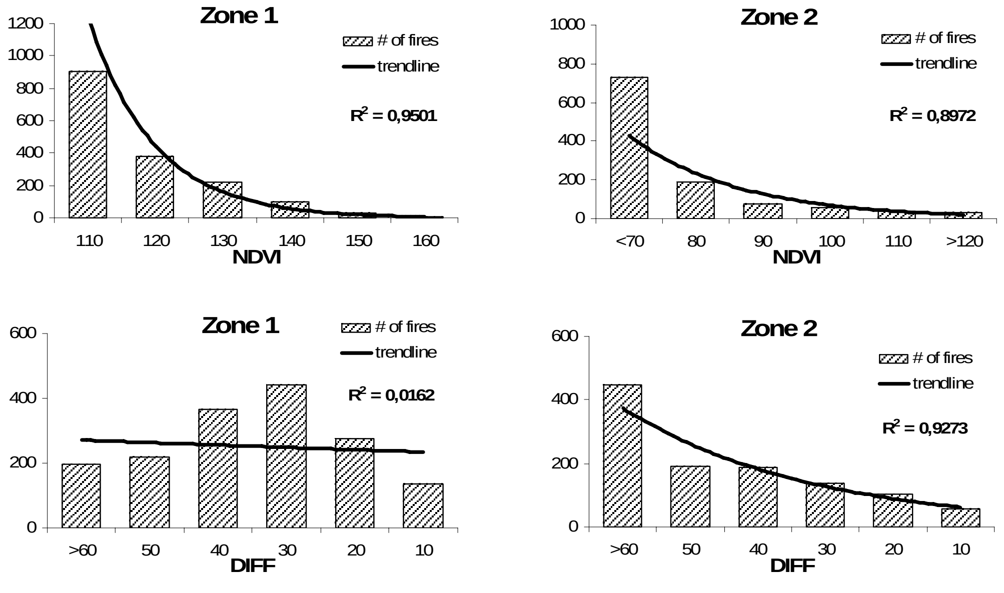


Figure 7.5: Average trend of FWI values

Thus, it is possible to observe how each considered index presents the tendency to assume highest levels of risk during the summer period, between July and September; exception done by the RGI in Zone1, the northern area of Spain. Moreover, also for the others indices derived by remote sensing, more related to the vegetation condition, Zone1 presents a slope of values less evident than Zone2. This could be interpreted as a consequence of the different climatologically condition between the two zones; which is also highlighted by a later beginning of the period of major stress. Concluding, this analysis could be considered as a graphical analysis in which it is possible to observe a correlation between levels of risk and period of major presence of forest fire occurrences. Nevertheless, no correlation between fire occurrences and index values could be derived. Moreover, there is no possibility to compare a graph of one index to the graph of another index to assess which one performs better.

Index re-classification, the index re-classification analysis would evaluate the potential of an index of forest fire risk observing the values of the index in presence of a fire occurrence. The hypothesis is that the goodness of an index of risk is valuable by considering relationship between number of fire events and values assumed by the index. Thus, an index would be judged reliable if most of the fires occurred when a high level of risk was pointed out by the index. Nevertheless, this analysis presents two problems. On one hand, it considers only values of the index over burnt areas. On the other hand, there are no rules to follow in order to exactly define how high level of risk should be represented by index values. The procedure most applied has been to study the events history and to classify the level of risk as a consequence of the observed information. The subdivision of the range of values assumed by an index into levels of risk is a consequence of the historical values of the index and thus strictly dependent by them. Following this simple procedure the observed values of the considered indices of risk were reclassified in six levels of risk; very low, low, moderate, high, very high and extreme. The following graphs highlight how easy is to reclassify each index of fire risk in order to produce good results (figure 7.6). Each graph presents the number of fires that occurred for a particular value of the index of risk during the study period. The values placed more at left represents higher levels of risk meanwhile values placed more at right represents lower levels of risk. As explained, for each index it was possible to derive a consequential high value of square correlation coefficient. The square correlation coefficient was obtained by using an exponential model in order to fit the number of fires to values of the index. Only the index based on the NVDI decrement produced a result different from the others. Nevertheless, this result is related to the low decrement presents in Zone1. If a finer range of values was considered, the obtained results would be better. For example, an improvement could be obtained by summing up all the occurrences having a value of the index bigger than 40. Nevertheless, these results are consequence of the procedure or reclassification; procedure that does not take into account of any other value of the index different from the one assumed during the fire. Thus, any procedure of comparison between different indices is difficult and not very reliable. For this reason, it is advisable to explore the potential of an index using directly the index values without introducing any process of reclassification.



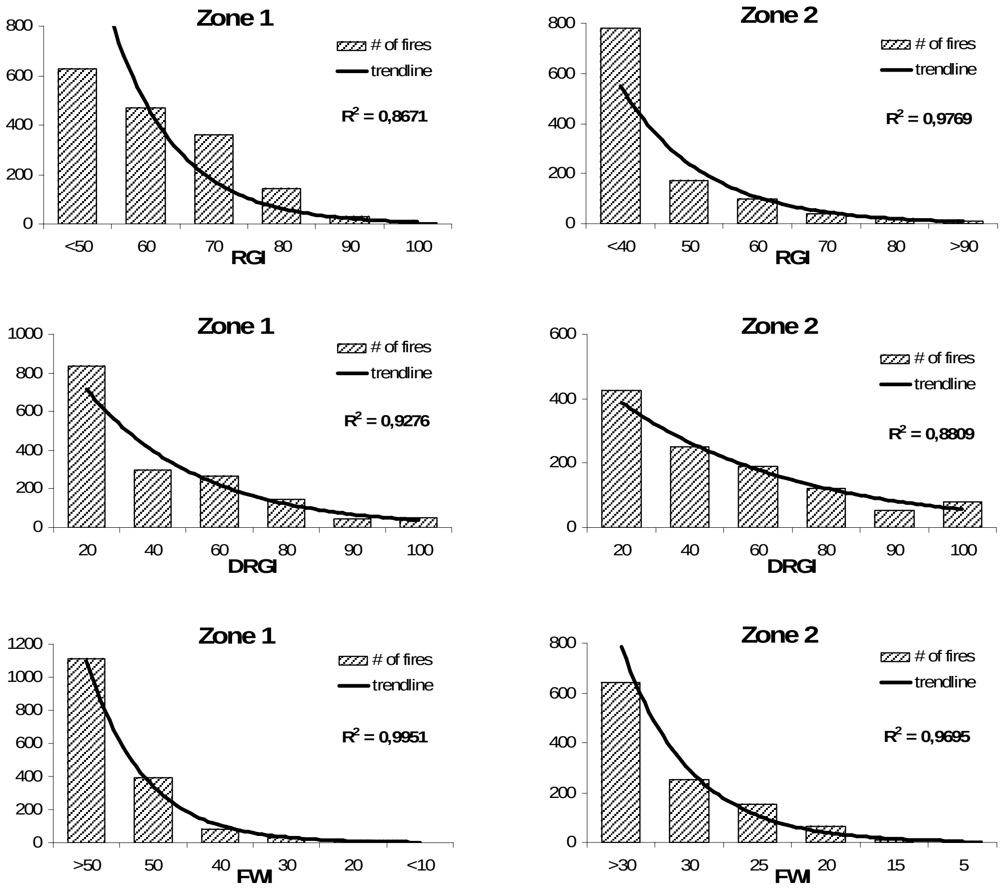


Figure 7.6: An example of an arbitrary index reclassification for the study indices

Index context, these analyses present a problem of evaluation linked to the context of analysis. On one hand, the average analysis is carried out considering the entire territory and it does not discriminate burnt areas from other areas. On the other hand, the reclassification process is carried out considering only values of the index belonging to burnt areas with no comparison with other values of the territory. However, these problems are the main points in the process of evaluation of the performance of an index of forest fire risk in order to understand if an index is able to discriminate levels of risk in an extended territory. To better explain the problem an example built over the available data is reported by chapter 1.4.1.3. Moreover, the data available permitted to observe the distribution of forest fires bigger than 50 hectares occurred in Spain during the study period (figure 7.7). The trend of forest fires occurrence is immediately noticeable; higher number of fires during the summer period, lower number of fires during the others months. A comparison between the number of fires and the average behaviour of the indices values (see previous section) pointed out a possible relationship; a major number of fires tend to occur where a higher level of index risk is present.

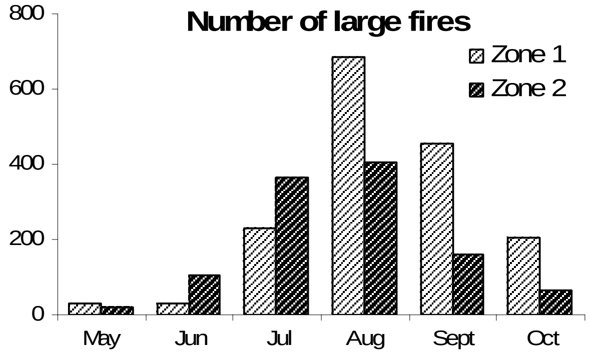


Figure 7.7: Distribution of forest fires bigger than 50 hectares occurred in Spain in the study period

Nevertheless, the presence of a high level of risk just the period before, or during, a fire occurrence it is a necessary but not a sufficient requirement in order to classify an index as a good index. In fact, if an entire territory was situated at the same level of risk at the same time, the indication furnished would be hardly useful. The index would furnish any added information more than the generally high level of risk for the entire territory. Consequently, it is not able to differentiate different areas in function of the risk status.

The performance index, it was introduced to evaluate the effective potential of an index of risk by comparing values over restricted areas to all the others values. This index estimates how much the information derived by the use of a particular index of risk is better than using a random value, the so called pure chance. As described in Chapter 5.7 the performance index was introduced by Mandallaz in order to better estimate the characteristics of a specific index. The introduction of the use of a random value in order to estimate the performance of an index permits the detachment of the obtained result from the index characteristics, as the range of values or the scale of reclassification and, thus, it permits a comparison of results obtained by different indices.

Qualitative analysis, the qualitative analysis adopted in this work permits to combine the two previous analyses. It compares the values of an index over burnt areas with the normal distribution of the values of that index. Thus, it analyses the values over burnt areas considering also values all over the territory. This analysis permits to verify the basis hypothesis that a fire tend to occur where a high level of risk is present. However, also this analysis does not permit an evaluation of the results more than the one furnished by a visual approach. The comparison between values over burnt areas and other values did not highlight evident difference between the two distributions of frequency. That is because during summer similar areas present similar characteristics. Assuming, for example, that NDVI could be used as a surrogate of vegetation stress, as shown in the reviewed literature, this stress could be consider similar on much of the Spanish territory and cannot be efficiently used as indicator of fire risk. If only areas that suffered fires were analyzed the conclusion extracted would have been that low NDVI values were correlated to fire occurrence. However, the analysis of the behaviour of NDVI in a large territory and in an extended time period showed that the NDVI itself does not have the capacity to discriminate levels of fire risk.

Different results were obtained by the use of FWI. In this case, a statistical difference between the distribution of values observed in burnt area and the general distribution of values all over the territory was observed. In particular, fire events tend to occur assuming a distribution of values centred on a higher value of FWI. This was interpreted as a tendency for a fire to occur assuming higher values of FWI; which are related to a high level of risk. Nevertheless, in both the cases, the qualitative analysis does not provide a method in order to quantify the difference in the distributions of values.

Statistical analysis, it has been deeply discussed regarding the importance to adopt a method of analysis of the indices able to assess the results numerically and independently by the adopted index the performance of this index. In the context of this work, the use of a statistical approach based on the performance index would solve that problem. This methodology evaluates day by day the value added in the estimate of fire risk given by a particular index. The analysis, carried out on six different indices of forest fire risk estimation, highlights interesting results. A part from some little difference in the behaviour during particular months, the indices derived by the NDVI presented really similar results. The adoption of the statistical analysis highlighted the worst performance of these indices during the summer period. In this period is visible a clear decrement in the ability of the indices in individuate areas more at risk. In particular, during August and September, it was observed a drop in the results. The NDVI-MVC index, the RGI and the DRGI gave an added value better than randomness in less than the 50% of the considered days.

Different results were obtained by the use of FWI. The performance index highlighted the ability of FWI to produce added information, better than randomness, in most of the observed days. In particular, the yearly analysis of the FWI demonstrated that it produced better results than using a random value in the 83% of the considered days in Zone1 and in the 82% of the considered days in Zone 2. The ratio performance index demonstrated the higher potential of FWI compared to the NDVI. The FWI presented results better than NDVI in all the cases, with the exception of the month of October in Zone 1. Even so, the results it produced were comparable to the ones obtained by the NDVI.

Concluding, for the first time it has been possible to quantify the results obtainable by the use of different indices of risk in the forest fire assessment. In particular, for the first time, it has been possible to quantify the better potential of meteorological indices over indices based on vegetation conditions.

Final remarks, this work carried out for the first time an extensive analysis of the results obtainable by the use of different indices in the field of forest fire risk assessment. In literature indices of risk have been frequently analysed to assess the vegetation status meanwhile have rarely considered in a context of forest fire risk assessment. Even though it was evidenced a relationship between vegetation status and fire risk, the obtained results are not always directly applicable in the assessment of forest fire risk.

This study investigates about existing relationships between values of risk and presence of large forest fires. For that aim, it is adopted for the first time an extensive set of information at country level; ten years of forest fire events all over the Spanish territory, which means a total of 3944 forest fire events and 6917 Spanish communes managed on about 8000 daily maps of risk, about 1600 for each considered index. This huge set of data required the creation of software able to manage it easily and furthermore quickly. For this reason specific JAVA classes were developed. Besides, an appropriate index of evaluation of the results is adopted in order to permit the first comparison between indices of risk derived both by remote sensing data and by meteorological information. Even though past studies assessed the results of different meteorological indices of forest fire risk, no studies have performed similar analysis between different indices of risk derived by remote sensing and, in particular, between indices of risk having different nature.

The results of this study demonstrated the remarkable potential of the meteorological information over remote sensing data in the assessment of forest fire risk. In particular, the FWI presents better aptitude to be adopted to discriminate a territory by different levels of forest fire risk. Even though results obtained by NDVI related indices of risk were not awful, these indices demonstrated a better ability in estimate the beginning of a period of particular risk of fire than in discriminate levels of risk in the territory. This is consequence of the fact that similar areas are subjected to similar level of vegetation stress and, consequently, they are placed at the same level of risk more or less at the same time.

It has been highlighted how results obtained by studying the condition of the vegetation are not immediately applicable to a forest fire context. In fact, while the results obtainable in the vegetation condition estimate are demonstrable by field works, the same is not possible in the context of forest fires where the presence of a high level of stress for vegetation does not assure the ignition of a fire. This point represents the key point of the analysis and justifies the generally low results obtained by remote sensing derived indices, and also by meteorological indices. In Europe forest fires are mainly caused by negligence or pasture burning and very few still remain naturals. Different conclusions would be derived if a particular level of fire risk implied the certainty of a fire ignition. Thus, this explains why the meteorological index performed better than remote sensing ones. While there is no strong correlation between fire ignition and vegetation condition, it was demonstrated how adverse meteorological conditions could heavy influence the fire propagation.

Concluding, the introduction of maps of risk at European level it is made possible by the introduction of remote sensing data and by a capillary network of weather stations. Nevertheless, due to their spatial resolution and to the discussed results of this work, these maps of risk could be only considered as an initial reference point in the prevention system. Forest fire is an extremely complex system in which the meteorological and vegetation conditions are only part of the influencing variables. Fire ignition, fire propagation and fire extension involved a multitude of variables which can not be regrouped forming a unique index of risk. Consequently, until the forest fire will be not became dependent only by naturals, and thus predictable, causes it is reasonable to expect similar results of performance also by the adoption of other indices of forest fire risk at global scale. The maps of risk have to be considered as one of the available tools. Nevertheless, the experience of the people working against forest fires still remains the fundamental tool of risk analysis. They know by direct experience the areas most at risk, the behaviour of a fire depending by the wind and the slopes of the territory and how to surround the fire in order to extinguish it. Nevertheless, every year some of those lost their life to fight a fire that in most of the case is caused by negligence and thus avoidable. For this reason it is important to improve prevention schemes year by year without disregarded them.

Future perspectives, the present work demonstrates the difficulty to extend local analysis to a global perspective. In particular, attention was done in the production of maps of forest fire risk adopting a European level. The results demonstrate a better performance of the use of meteorological data over remote sensing data. The possibility to dispose of meteorological information at better level of detail could further improve the goodness of derived indices of risk. Moreover, better results could be obtainable by the introduction of a meteorological index build on Mediterranean vegetation instead of American conditions.

Even though the NDVI did not provide significant results, it would be advisable to continue working on it, in particular in its introduction in a more complex indices based on meteorological and remote sensing derived variables; which would improve the individual results.

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Appendix A

Acronyms

API	Advanced Programming Interface
AVHRR	Advanced Very High Resolution Radiometer
BISE	Best Index Slope Extraction
BUI	BuildUp Index
CCD	Common Core Database
CORINE	Coordination of information on the environment
DC	Drought Code
DG-AGRI	Directorate General for Agriculture
DIFF	Difference Index
DMC	Duff Moisture Code
DRGI	Dynamic Relative Greenness Index
DSR	Daily Severity Rating
EC	European Commission
EEC	European Economic Community
EFFIS	European Forest Fire Information System
EU	European Union
FAO	Food and Agriculture of the United Nations
FFMC	Fine Fuel Moisture Code
FPI	Fire Potential Index
FWI	Canadian Fire Weather Index
GAC	Global Area Coverage
HRPT	High Resolution Picture Transmission
ISI	Initial Spread Index
JAI	Java Advanced Imaging
JRC	Joint Research Centre
LAC	Local Area Coverage
MID	Middle Infrared
MVC	Maximum Value Composite
MVI	Maximum Value Interpolated

NDVI	Normalized Difference Vegetation Index
NDWI	Normalized Difference Water Index
NFDRS	National Fire Danger Rating System
NIR	Near Infrared
NOAA	National Oceanic and Atmospheric Administration
RGI	Relative Greenness Index
SAVI	Soil Adjusted Vegetation Index
SWIR	Short Wave Infrared
WWF	World Wide Fund for nature

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Abstract

Forest fires are a major hazard to Mediterranean forests where, on average, half a million hectares of forested areas are burned every year. It is for this reason that the assessment of fire risk lies at the heart of fire prevention policies in the region. Often, the estimation of forest fire risk involves the integration of meteorological and other fuel-related variables leading to an index that assesses the different levels of risk. Two indices that are frequently used to estimate the level of fire risk are the Fire Weather Index (FWI) and the Normalized Difference Vegetation Index (NDVI). Although the correlation between the number of fires and the level of risk determined by the indices has been demonstrated; however the analysis that lead to this conclusion considered only the areas where the fires took place. The present paper analyzes the behaviour of these fire risk indices both in areas where fires took place and in those where fires did not occur. It analyzes and compares the potential of the two indices to discriminate different levels of fire risk over large areas using quantitative and graphical methods. The analysis is performed considering a dataset of 10 years of fire events, satellite data and meteorological data for Spain. The results show a better performance of the FWI over NDVI in identifying areas at risk of fires.

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