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Fire risk mapping by integration of dynamic and structural variables

Mário R. Caetano, Sérgio Freire & Hugo Carrão
Portuguese Geographic Institute (IGP), Rua Artilharia Um, 107, Sala 4.08, 1099-052 Lisboa, Portugal
mario.caetano@igeo.pt

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ABSTRACT: A methodology for fire risk mapping using satellite imagery and ancillary data, developed within PREMFIRE, a project funded by European Space Agency (ESA), is presented. The proposed methodology is based on the combination of both structural and dynamic indices to produce an Integrated Forest Fire Risk map, to be updated daily. The structural component is based on the combination of geographical variables that do not change in a short lapse of time or that are human-related, such as vegetation cover (fuel types), topography, and distance to roads and urban areas. Therefore, to be realistic, this index needs to be updated only at the beginning of the fire season. The dynamic fire risk index aims at detecting slight and constant variations in the flammability of forest fuels during the fire season and hence makes use of variables that, however changing in a short lapse of time, can still be measured. The approach combines a fuel model map, a maximum live ratio map, a relative greenness map and a 10-hour timelag dead fuel moisture map. The integration of both structural and dynamic indices was achieved by creating a fire risk table, where specific risk values were assigned to all possible combinations, resulting in values ranging from 1 to 3, where 1 means low risk, 2 medium risk, and 3 very high risk. Final results on the validation of the integrated risk model for a study area in central Portugal and for the 2001 fire season are also presented. The results obtained show that the model developed, designated as Integrated Forest Fire Risk (IFFR), identifies well those areas at risk. The model explains adequately fire occurrence, since high-risk value situations have shown an excellent relation with burnt areas.

1 INTRODUCTION

Considerable areas of the Portuguese forest are affected annually by fires, depending upon moisture and temperature conditions, thus having an important environmental and economic impact in the country. In this way, Portugal is still one of the Mediterranean countries that has been most affected by forest fires in recent years, having one of the highest percentages of burned forest in Europe.

Although forest fire occurrence is almost always a result of the combination of several factors, it is apparent that climate and human activities have a major influence on fire events in the Mediterranean region. High temperatures and almost absence of precipitation during the summer (dry summers) are responsible for a period of plant stress, when the moisture of plants decreases dramatically and consequently their degree of flammability increases. In the case of Portugal, arson is also a very significant cause of fires, due to powerful economic interests involving forest land. Considering that all these situations frequently occur in Portugal, fire occurrence becomes very difficult to forecast. However, it is obvious that fire-fighting is more difficult and expensive than its prevention and so it becomes particularly important to develop effective methods to support forest fire prevention.

In order to identify guidelines for increasing and optimizing the contribution of Earth Observation (EO) derived information for forest fire prevention, the European Space Agency (ESA) has been funding fire-related research projects in several European countries. In this paper we present a study carried out within the PREMFIRE project, sponsored by ESA, for the research and development of the most adequate method for implementing a real-time fire-fighting system for the prevention and mitigation of forest fire hazard in Portugal. This specific study concerns the research and development of a methodology for fire risk mapping in Portugal, which can be used in the field to support fire pre-suppression and suppression activities.

1.1 *Fire risk modeling and assessment*

Fire risk, fire potential, or fire danger indices are all attempts at accurately quantifying the likelihood of a fire event taking place when there is an ignition source, or simply estimating a probability of fire starting. Developing a fire danger index involves taking into account a wide range of factors, most commonly weather, fuel, and topography (Deeming *et al*., 1977). The choice of variables and the different ways they are combined result in a multiplicity of approaches to fire risk mapping. Given the various approaches to the challenge of forest fire risk assessment, several solutions to the classification of fire risk methods have been proposed. One of the latest approaches to classification, by the European Union's (EU) Joint Research Center (JRC, 2001), suggests a broad grouping of indices or methods according to their temporal scale:

- *Structural* or *long-term* indices are derived from factors that do not change in short lapse of time, i.e. topography or land-cover;
- *Dynamic* or *short-term* rely on parameters that change fairly continuously over time, i.e. vegetation condition or weather;
- *Integrated* or *Advanced* indices would include both structural and dynamic variables.

A structural forest fire risk index is based on the combination of geographical variables that do not change in a short lapse of time or that are human-related. This index can be calculated using several types of variables, including vegetation cover (fuel types), topography, elevation, slope, aspect, climate, roads, soils, fire history, and population density (Chuvieco and Congalton, 1989; Salas and Chuvieco, 1992; Chuvieco and Salas, 1996; Aranha and Alves, 2001; Aranha *et al*., 2001). Thus, to be realistic this index needs to be updated only at the beginning of the year's fire season. It is more oriented to account for ignition risk and so can be computed before the fire season to improve more permanent planning of fire-fighting activities and surveillance.

The choice and importance of the different variables is usually determined after a study of correlation between the parameters and fire history of the area, over a significant period, is conducted. Due to the fact that the causes of fire can vary significantly across space, these relationships are valid over a limited area and therefore these indices usually have mostly local or regional application. However, most indices do not include the spatial distribution of human-related fire risk due to the difficulty in modeling human behavior activities, such as recreation or arson (Vasconcelos *et al*., 2001). An approach to overcome this difficulty has been to model the spatial distribution of human risk indirectly, based on ancillary variables like accessibility or fire incidence (Chuvieco and Congalton, 1989; Salas and Chuvieco, 1992; Chuvieco and Salas, 1996; Aranha and Alves, 2001; Aranha *et al*., 2001).

A dynamic fire risk index aims at detecting slight and constant variations in the flammability of forest fuels during the fire season and hence makes use of variables that, however changing in a short lapse of time, can still be measured. Fuel models provide a quantitative description of several physical and chemical properties of vegetation types and their knowledge can be used in a mathematical fire model to calculate how a specific vegetation type will burn under various environmental conditions (Albini, 1976; Rothermel, 1972; Rothermel *et al*., 1986). The amount, distribution and continuity of vegetation and wood are critical variables for fire danger prediction (Bradshaw *et al*., 1983; Chuvieco and Martín, 1994), since the degree of flammability of vegetation is dependent on the amount of dead and live fuels and their moisture content. However, the vegetation's moisture content that is relevant to combustion varies with meteorological conditions for each fuel type (assigned a fuel model) and is also related to its "greenness" or plant vigor. Therefore, an effective dynamic fire model should be computed daily by combining an updated and reasonably detailed fuel model map with relevant meteorological variables (such as temperature, precipitation, relative humidity, solar radiation and wind) and with an estimate of the amount of dead and live fuels.

An integrated approach is based on the assumption that the start and progression of a forest fire is affected by different factors, therefore calling for their integrated analysis (Chuvieco and Congalton, 1989). Such an approach was recently suggested by the Joint Research Centre of the EU – JRC (JRC, 2001), but has not yet been fully developed and implemented by that research institution. The most critical problem with this approach is how to establish a coherent criterion to effectively combine the relevant variables. Frequently, the integration of both structural and dynamic variables is based in the specific knowledge of experts, thus resulting a procedure prone to subjectivity and local orientation.

The proposed methodology for forest fire risk mapping for Portugal is based on the combination of both structural and dynamic indices to produce an integrated fire risk map, to be updated daily. The following methodology was adopted after carrying out a review of existing approaches to forest fire risk modeling and mapping and was tested in a study area in Portugal. We present a methodology to produce a daily fire risk map using satellite imagery and ancillary data. During this assessment, it was concluded that an approach combining both "static" geographic variables with dynamic factors in a single fire risk index value would yield the best results and would be the most useful and efficient for prevention and mitigation of forest fire events. The structural component is mainly based on Chuvieco and Congalton (1989). The dynamic component is adapted from Burgan and others (Burgan *et al*., 1998; Klaver *et al*., 1997; Lopéz *et al*., 1997), to Portugal and to existing data sets. This method is based on an updated land cover map, being the structural index computed at a 25-meter spatial resolution, and the dynamic index at 550 meters, which is also the resolution of the final integrated index.

2 METHODOLOGY

2.1 *Study area*

For testing and implementing this methodology, a study area was selected based on: 1) frequency of forest fires in the 2001 fire season and corresponding burnt area (DGF, 2001), for validation purposes; 2) landscape and forest species diversity; 3) impossibility of having more than one Landsat image. In this way, the study area chosen is located in central Portugal and has a total surface of 1.391.000 ha that corresponds to the districts of Castelo Branco, Guarda, Viseu, Coimbra, Bragança, and Vila Real (Fig. 1). This area comprises 665 communes contained within the Landsat TM 203/32 path/row limits. This region is geographically diverse, providing an excellent test ground for the methodology. Elevation ranges from 50 to 1990 m, including the highest region of mainland Portugal, and slopes vary from smooth to very steep. The area has the typical characteristics of a Mediterranean environment, being affected by an intense summer drought. However, the climate of this area is greatly influenced by its topography, being characterized by medium-to-high temperatures and low-to-medium rainfall that tend, respectively, to decrease and increase with altitude. Regarding the land cover, 70% of the area is occupied by forest, 15% by agriculture (non-irrigated arable lands, permanent irrigated lands, olive trees, vineyards and fruit trees) and 12% by bare ground. The vegetation is very diverse, with extensive areas of *Pinus pinaster*, *Eucalyptus globulus* and some areas of *Pinus pinea* that had replaced most of the original forests of *Castanea sativa*, *Quercus pyrenaica* and *Quercus faginea*. The cork oaks *Quercus suber* and *Quercus rotundifolia* are also present in this region, since they are typical of Mediterranean areas. Several types of xerophytic and resinous shrubs, such as *Cytisus sp.*, *Retama sp.*, *Cistus sp.*, *Erica sp.* or *Genista sp.*, with resistant leaves and/or high resinous – and therefore high flammable – are spread throughout the study area. According to those characteristics, this area has a high potential danger of suffering fire during the fire season, considering that it has also been severely affected by forest fires in the past.

Figure 1. Location of the study area.

2.2 *Structural fire risk*

The development of a structural forest index can be executed using several types of variables, whose choice and importance is usually determined after a study of correlation between those variables and the fire history over a significant period. However, a correlation study of this nature is always a major undertaking and was not planned within the framework of the PREMFIRE project. Therefore, a specific set of variables and corresponding weights were not calculated for Portugal. Given these constraints, we elected to adopt the variables that were considered and tested by several authors (Chuvieco and Congalton, 1989; Salas and Chuvieco, 1992; Chuvieco and Salas, 1996; Aranha and Alves, 2001; Aranha *et al*., 2001), as being the most influential in forest fire occurrence in the Mediterranean basin. These authors, in order to classify fire risk areas in the Mediterranean coast, selected the following set of variables: elevation; slope; aspect; proximity to roads, trails and urban areas; fuel-oriented vegetation classes.

The combination of the presented variables, for the evaluation of the Structural Fire Index (SFI), can be expressed as (adapted from Chuvieco and Congalton, 1989):

$$SFI = 100v + 30s + 10a + 5u + 2e \tag{1}$$

where v, s, a, u, and e represent, respectively, vegetation, slope, aspect, proximity to roads and urban areas, and elevation. Each of these variables is considered as a different layer of information and the overlay of all the variables makes it possible to define fire danger levels within the study area.

In Portugal, it was necessary to produce an updated fuel-oriented vegetation map for the study area, due to the fact that the existing land cover maps are outdated – Corine Land Cover map with a Minimum Mapping Unit (MMU) of 25 ha dates from 1987 and the detailed Land Cover Map of 1990 (COS'90), with a MMU of 1 ha was derived from aerial photography acquired in 1990/1991. A new land cover map for 2001 and for the study area, with a spatial resolution of 25-meters, was produced using a Landsat 5-TM image, acquired in April 9 2001 (WRS 203/32), combined with ancillary data (Freire *et al*., 2001), namely the detailed COS'90. Land cover types susceptible to wildland fires, which also included pastures and olive trees, were selected from this map and used as a basis for calculating the structural fire index map. A danger index value was not assigned to water, urban land, remaining agricultural areas, and to all other non-natural and non-vegetated areas, as these cannot be included on the concept of forest fire danger. Topographic variables were derived from the Digital Terrain Elevation Data (DTED) representing 25-meters pixels produced by the Portuguese Army Geographic Institute (IGeoE). Roads were extracted from the vector 1:250 000 road map produced by IGeoE, and urban areas from the COS'90 vector theme. Both were converted to raster format representing 25-meters pixels.

In the case of Portugal, where arson is a very significant cause of forest fires, the authors feel that the structural component of an integrated index should try to account for human activity. However, such a modeling effort has little or no support in the literature, most probably because human behavior is extremely difficult to model. Still, arsonist activity could be, to a limited extent, accounted for by mapping roads and trails used for access and as escape routes.

2.3 *Dynamic fire risk index*

A dynamic fire risk index aims at detecting variations in the flammability of forest fuels during the fire season, considering a set of parameters that change fairly continuously over time, i.e. vegetation condition or weather. One such dynamic index is the Fire Potential Index (FPI) model, which was recently developed in the USA to incorporate both satellite and surface observations in a danger index (Burgan *et al*., 1998; Klaver *et al*., 1997). This method was tested in California and Nevada and correlates well with fire occurrence, and can be used to map fire danger from national to local scales by using a geographic information system. Test areas also included Spain, Chile, and Mexico (Klaver *et al*., 1997). This approach is being adopted for European conditions under the designation of IAFFRI – Integrated or Advanced Forest Fire Risk Index (JRC, 2001), and was recently tested in Portugal, Spain, Italy and France showing good correlation with fire events (Lopéz *et al*., 2001). Due to the good performance of this new method, we adopted the FPI approach to Portugal and to existing data sets.

The inputs to the FPI model are a fuel model map, a maximum live ratio map, a relative greenness map (Burgan and Hartford, 1993) and a 10-hour timelag dead fuel moisture map (Fosberg and Deeming, 1971). In this study, inputs to the model were provided in raster format and as byte data representing 550-meter pixels. The choice of this spatial resolution reflects a balance between detail of available data sets and operational constraints concerning processing time, and is also appropriate to the configuration of the Portuguese network of weather stations.

At the base of the FPI is an updated fuel model map (Albini, 1976; Rothermel *et al*., 1986; Rothermel, 1972), in which values of extinction moisture of dead fuels are assigned to each fuel class. The fuel model map used as a basis for calculating the FPI was derived from the 2001 updated land cover map (see Chapter 2.2), in which only the land cover types prone to wildland fires were considered. The relationship between these land cover types and the fuel models nomenclature (Albini, 1976; Rothermel *et al*., 1986; Rothermel, 1972) was investigated, and a fuel model and a dead fuel extinction moisture value was assigned to each one. In order to meet the FPI requirements, this map was converted to a spatial resolution of 550-m.

The maximum live ratio and the relative greenness were assessed using the popular Normalized Difference Vegetation Index (NDVI) (Rouse *et al*., 1973), which was computed from imagery obtained by the Advanced Very High Resolution Radiometer (AVHRR) on board the National Oceanic and Atmospheric Administration (NOAA) polar orbiting satellites. Maximum and minimum NDVI values for the period 1995 – 2001 and daily NDVI maps for the 2001 fire season were provided by the JRC as 4.4-km raster data sets. However, in order to meet the desirable resolution, the original data were transformed into a regular matrix with 550-m cells. The Maximum Live Ratio Map (LRmx) was then derived as (Burgan *et al*., 1998; Lopéz *et al*., 2001):

$$LR_{mx} = \left[0.25 + 0.5 \times \left(ND_{mx} / ND_{absmx} \right)\right] \times 100 \tag{2}$$

where NDmx – Historical maximum NDVI value for a given pixel; NDabsmx – Historical maximum NDVI value for the study area.

Relative greenness (RG) was computed by comparing, for each pixel, the current NDVI values and the available historical range (1995-2001) of NDVI data. Specifically the algorithm is (Burgan and Hartford, 1993):

$$RG = (ND_0 - ND_{mn}) / (ND_{mx} - ND_{mn}) \times 100 \tag{3}$$

where ND_0 – Highest observed NDVI value for current 10-day composite period; NDmn – Historical minimum NDVI value for a given pixel; NDmx – Historical maximum NDVI value for a given pixel.

The 10-hour fuel moisture map was produced based on temperature, relative humidity, previous precipitation and state of the weather (cloudiness and occurrence of precipitation) values. The meteorological data used for its estimation was collected by the Portuguese Meteorological Institute (IM) net-

network of 76 weather stations, daily at 12h00 local time between June 1 and September 30 of 2001. The meteorological variables were combined for each weather station according to Fosberg and Deeming (1971), resulting in a 10-hour fuel moisture value, in percentage, that was interpolated across the landscape to meet the model's requirements of 550-m resolution data. The 10-hour fuel moisture values computed for each weather station were interpolated using an inverse distance square algorithm, considering 6 neighbors (Hartkamp *et al.*, 1999; Wilson, 1996). This method does not account for influence of topography on fuel moisture, but given that the synoptic network is relatively dense and has weather stations at both low and high elevations, the resulting interpolation seem reasonably appropriate.

In Portugal, the Fire Potential Index was computed as a raster map with a spatial resolution of 550-m and presenting values that can range from 0 to 100. Ideally, the index will be computed daily and can be provided as forecast by updating its meteorological component, which is straightforward to produce when weather forecast data is available for 1 to 3 days. As in the original methodology (Burgan *et al.*, 1998), the FPI was computed as follows:

$$FPI = \left[(1 - TN_f) \times (1 - LR)\right] \times 100 \quad (4)$$

where TNf – Fractional ten hour fuel moisture; LR – Live fuel ratio.

2.4 *Integrated forest fire risk index*

The proposed methodology for forest fire risk mapping for Portugal is based on the combination of both structural and dynamic indices to produce an Integrated Forest Fire Risk (IFFR) map, to be updated daily. Since the goal of this approach is to integrate and combine the structural and dynamic indices into a single fire risk map, both their original and ordinal scales were reclassified to nominal-categorical, in order to lower the difficulty of their combination. Given that this is a new approach, this reclassification was possible only after testing and validating those indices in a study area in Portugal, in order to investigate for each one the gradients of risk and their correlation with actual fire events. The combination procedure was developed creating a fire risk table, where specific danger values were assigned to the combinations of the two categorical variables. The results and validation of this methodology will be presented in the next section.

3 RESULTS AND VALIDATION

The validation process consisted on the statistical analysis of the relation between fire risk indices and burnt areas, their date and point of ignition, in order to develop a daily Integrated Forest Fire Risk (IFFR) based upon that analysis.

For validation purposes it was necessary to digitize burnt areas within the study area for the fire season of 2001. Using the MapUp software (Nunes *et al.*, 1997) with the Landsat 5-TM and Landsat 7-ETM images (WRS 203/32) acquired, respectively, in April 9 2001 and November 11 2001, it was possible to identify and map areas showing vegetation greenness decrease during that period, such those affected by forest fires or forest cuts. However, areas smaller than 5 ha were not considered due to limitations in satellite imagery resolution (25 m) used for their digitalization. Through visual analysis this map was improved and burnt areas were located and selected from all mapped areas with vegetation decrease. The final burnt area map in vector format was converted to raster format and then was overlaid to the structural fire risk map. This procedure allowed the performance of statistical analyses of the correlation between fire occurrence and the SFI for the study area and for 2001 fire season.

In order to examine the relationship between FPI and IFFR and fire occurrence it was necessary, in addition to the mapped burnt areas, to calculate fire density for both indices. Fire density was determined for FPI and IFFR classes by dividing the number of fires that had occurred in each index class by the total number of cells in each class during fire season. The geographic location of daily fire starting points was produced using a database provided by *Direcção Geral das Florestas* (DGF) with the geographic location of 2362 fires that had occurred during the 2001 fire season in the study area. Since the geographic location of each point did not correspond to the real fire starting point but to an assumed starting point (evaluated by the fire service in the field), both FPI and IFFR values for each fire were considered as being the maximum value within the commune where it had occurred. The total number of cells for each index was then evaluated considering only those communes with at least one fire during the designated fire period. The rate of change of both FPI and IFFR mean values for each mapped burnt area four days before fire events was also evaluated. This procedure was carried on by combining the digitized burnt areas with the fire points provided by DGF in order to assign to each area the most likely fire date or dates, according to the geographical location of both areas and points. However, only areas greater than 30 ha were considered. This option was due to the fact that the spatial resolutions of FPI and IFFR (550 m) is smaller than the SFI resolution (25 m), and their pixel area is of approximately 30 ha.

Based on this process, 359 burnt areas greater than 5 ha within the study area and for the fire season of 2001 were identified and analyzed, representing 22 936 ha. Fig. 2 shows the SFI histogram for the study area and the total burnt area classified according to SFI values. Considering the figure chart it is possible to distinguish three intervals in the distribution of SFI values, respectively between 0 and 100, 100 and 200, and between 200 and 255. These results are in agreement with the ones obtained by Chuvieco and Congalton in 1989, which suggested that SFI values should be divided in three risk classes, whose limit values correspond exactly to those obtained in the current study. In this way, SFI was divided in the three-presented classes and was analyzed by relating these classes with burnt areas. The results are presented in Table 1 and according to its values one can state that the high fire risk class is the most represented in study area, followed by low and medium fire risk classes, respectively. However, burnt area and ratio burnt area/total area do not follow the same distribution, since medium risk is more representative then low risk. This fact confirms that burnt area reflects fire risk levels of SFI instead of landscape structure, in which burnt area is greater for low risk than for medium risk. These results suggest that this index is potentially a valuable fire risk assessment tool for the study area.

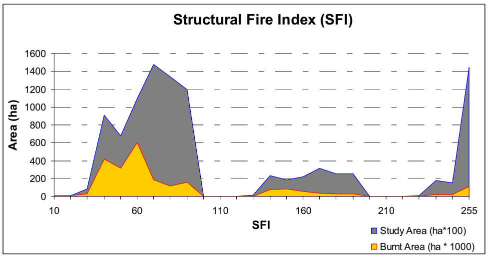

Figure 2. Structural Fire Index Histogram.

Table 1. Total area, burnt area and ratio burnt area/total area for each SFI class.

SFI	Total area (ha)	Total area (%)	Burnt area (ha)	Burnt area (%)	Burnt area/ Total area (%)
0 - 100	678802	67.6	18359	80	1.8
101-200	147524	14.7	3119	13.6	0.3
201 - 255	178365	17.7	1458	6.4	0.1
Total	1004691	100	22936	100	2.2

Considering only the digitized burnt areas greater than 30 ha, it was possible to study the rate of change of daily mean FPI values four days before fire events. Fig. 3 shows mean rate of change of maximum FPI values and respective standard deviation for all digitized burnt areas four days before fire events. It shows that FPI mean daily values increase in the days closer to the fire events. It is also visible that the slope of the FPI values becomes steeper two days before fire occurrence.

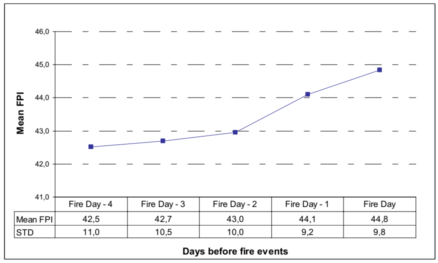

Figure 3. FPI average and standard deviation values for burnt areas greater then 30 ha four days before fire events.

Another important observation is the one related with fire density, presented in Fig. 4. One notices that the dynamic fire risk, evaluated by the FPI, increases as well as fire density increases, although the FPI values show a normal distribution in the study area centered in a value near 40.

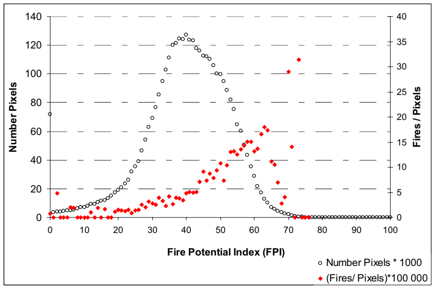

Figure 4. FPI fire density and total number of pixels for the study area during 2001 fire season.

After these analyses it was possible to combine SFI and FPI risk maps to produce an Integrated Forest Fire Risk map (Fig. 5). The most critical problem with this approach is to establish a coherent criterion to effectively combine those indices. Since the goal of this approach is to integrate and combine the structural and dynamic indices into a single fire risk map, a qualitative scheme was adopted, and both their original and ordinal scales were reclassified to nominal-categorical, according to Tables 2 and 3, respectively. Each of these categorical classes represent a level of forest fire risk and their integration was achieved by using a fire risk table (Table 4), resulting in integrated risk values ranging from 1 to 3, where 1 means low risk, 2 medium risk, and 3 very high risk. The method and weights for combining the structural model with the dynamic index were only decided on the final stage of this validation. The combination of medium and high structural risk values with very high and high/very high dynamic risk values, respectively, results in an integrated very high risk. On the other hand, the combination of low and medium structural risk values with low/medium and low dynamic risk values, respectively, results in an integrated low risk. To the remaining combinations an integrated medium risk is assigned. The defined combinations show that both structural and dynamic indices have similar weights on scaling the integrated forest fire risk. This was considered as being the best solution for their integration regarding validation results and considering that both have an important role on forest fire risk. The former identifies those spatial scenarios most prone and vulnerable to fire occurrence and to its effects at the beginning of the fire season, while the last limit those areas, during fire season period, according to daily vegetation status and meteorological conditions.

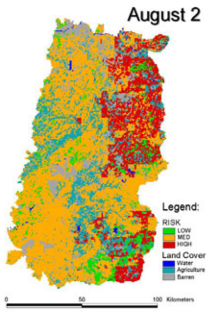

Figure 5. Integrated Forest Fire Risk (IFFR) map for study area and for 02/08/01.

Table 2. Structural Fire Index Reclassification.

SFI	Class	Coefficient
0 – 100	High	3
101 – 200	Medium	2
201 – 255	Low	1

Table 3. Fire Potential Index Reclassification.

FPI	Class	Coefficient
0 – 20	Low	1
21 – 40	Medium	2
41 – 60	High	3
61 – 100	Very High	4

Table 4. Integrated Forest Fire Risk.

SFI	FPI			
	1	**2**	**3**	**4**
1	1	1	2	2
2	1	2	2	3
3	2	2	3	3

Fig. 6 shows fire density rate of change according to IFFR values. It is obvious that, in addition to the fact that fire density is about zero in low fire risk class, its values increase almost four times from medium to high fire risk class, although the total surface represented by high risk is smaller than by medium risk. These observations prove that this method fits the characteristics of the study area and that fire risk can be evaluated based on its values.

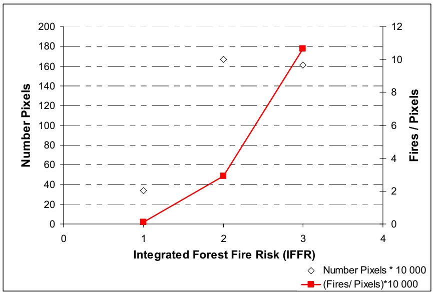

Figure 6. IFFR fire density and total number of pixels for the study area during 2001 fire season.

The mean rates of change of IFFR maximum values for each burnt area, four days before fire events, are presented in Fig. 7. This information supports the previous observations, since it shows a steeper increase of IFFR values before fire occurrence, especially two days before.

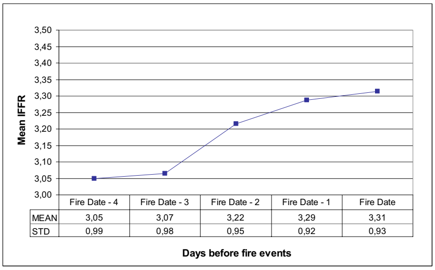

Figure 7. IFFR average and standard deviation values for burnt areas greater then 30 ha four days before fire events.

4 CONCLUSIONS

According to the results obtained, one can state that a method that combines a structural with a dynamic index for the pioneer development of daily integrated fire risk maps, based on satellite imagery and ancillary data, can support a system for the prevention of forest fires in Portugal. The proposed methodology is oriented for the development of three different products, which can be used together or individually by forest prevention services during fire prevention and mitigation planning activities. The results of the computation of these indices in the study area have shown their ability to identify potential fire scenarios. All indices appear to have predicted fire situations, since most of burnt areas occur on high-risk class areas. Once again, the lack of historical data, namely related to historical fire occurrence within study area, did not allow the development of a more consistent relation between index values and fire occurrence areas.

It is important to note, as final statement, that several future improvements can be made within this approach in Portugal, namely:

1. Development of fuel models and respective dead fuel moisture extinction values more specifically related to forest classes used in land cover maps available in Portugal;
2. Consider the use or combination of NDVI data from new sensors with spatial resolution of 1-km or greater, and identification of the suitable historical period for the acquisition of maximum and minimum NDVI values;
3. Optimization of best interpolation methods for 10-hour timelag dead fuel moisture estimation;
4. Identification and inclusion of variables representing human behavior in feasible models of fire risk.

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