Forest Fire Potential Index for Navarra Autonomic Community (Spain)

Margarita Huesca Martínez[1], Alicia Palacios-Orueta[1], Fernando Montes[1], Ana Sebastián[2], Paula Escribano[3].

Abstract

This study presents the development of a Forest Fire Potential Index at a regional scale for the Autonomic Community of Navarra at 500 meters spatial resolution. The index developed is based on the Fire Potential Index (FPI) applied by Sebastián (2001) at European scale and designed originally by Burgan (1998). The FPI is a dynamic Forest Fire Potential Index based on fuel characteristics and moisture status. The FPI uses the extinction moisture from fuel type map, the ten-hour timelag dead fuel moisture from meteorological data (temperature and relative moisture) and green vegetation percentage from Relative Greenness Vegetation Index. This research investigates the suitability of NDWI derived from MODIS satellite images to assess fire potential, and compares it with NDVI. The study period lasts from February 2000 to December 2005. The output of the model ranges between 1 and 100 and it is updated every eight days. The result of this study shows the usefulness of MODIS SWIR information for characterizing fire potential dynamics at a regional scale. In the bioclimatic Mediterranean region average values of both indexes (FPI_{NDVI} and FPI_{NDWI}) explain the uni-modal behaviour of forest fires typical of this area. In addition, both show a good correlation between forest fire potential and fires occurrence. In the Atlantic bioclimatic region FPI_{NDWI} explains better the bi-modal behaviour of forest fires than FPI_{NDVI}. Thus, this indicates that NDWI is a useful vegetation index for estimating forest fire potential in the Atlantic region.

Introduction

Forests play an important role in the environment (Morgan et al., 2001). In Spain, forest fires are one of the main causes of destruction of natural resources, representing a threat for forest sustainability and for human life, therefore, forest fire potential estimation is one of the main concerns of the Spanish Environmental Administration. Fire danger indexes which are used to assess fire potential (Velez, 2000) take into account a wide range of factors like weather, fuel, and topography (Deeming et al., 1978).

Water status of live vegetation is one of the main factors in affecting forest fire behaviour (Verbesselt et al., 2002), one of the reasons is that high moisture content increases the heat required to ignite a fuel (Maki et al., 2004) in addition, this is a particularly difficult parameter to estimate (Chuvieco et al., 2004). Scientists have studied and evaluated vegetation stress based on the Normalized Difference Vegetation Index (NDVI) (Chuvieco et al., 2002; Illera et al., 1996; Verbesselt et al., 2002) which is probably the index most frequently used for this purpose. The relationship between surface temperature and the NDVI is strongly correlated to surface moisture status (Verbesselt, et al., 2002; Alonso et al., 1996, Chuvieco et al.,

[1] ETSI Montes - UPM.
[2] Dirección General de la Conservación de la Naturaleza.
[3] Universidad de Almería.

1999, Chuvieco et al., 2003). Thus, vegetation greenness provides a useful parameterization of the vegetation moisture content (Burgan et al., 1998). Also several studies indicate the relationship between vegetation water status and the information obtained from the shortwave-infrared (SWIR) (Khanna et al., 2007) domain due to the broad fundamental absorption band of water at 2.8 microns. Hence, it has been found a clear relationship between Normalized Vegetation Water Index (NDWI) and fuel moisture content (Ceccato et al., 2001; Zarco Tejada et al., 2003; Danson and Bowyer, 2004).

Advanced Very High Resolution Radiometer (AVHRR) information has been used often in forest fire research because of the availability of thermal band and high acquisition frequency (Sannier et al., 2002: Gonzalez-Alonso et al., 1997; Aguado et al., 2003). The Moderate Resolution Imaging Spectroradiometer (MODIS) sensor on the TERRA satellite improves the spatial and the spectral resolution provided by AVHRR. The availability of the SWIR spectral region allows estimating parameter related to moisture (Fensholt et al., 2003).

The moisture content of small dead fuels is an essential parameter on forest fire ignition (Viney et al., 1990). Several studies have shown a high correlation between dead fuel moisture content with fire occurrence (Gomes et al., 2006; Pedrosa et al., 2006). Dead fuels are more dangerous than live vegetation because they are drier and more atmospheric dependent, (Verbesselt et al., 2006) so that they respond to atmospheric moisture faster than live vegetation, whose moisture content is also controlled by physiological activity (Sun et al., 2006).

The Fire Potential Index (FPI) (Burgan et al., 1998) combines meteorological and remote sensing data integrating satellite and surface observations (Burgan et al., 1998). This index has showed a high correlation with fire occurrence in California and Nevada; it has been tested also in Europe showing good results in the Mediterranean region (Sebastián et al., 2001).

The main goal of this research is to apply the actual FPI index at a regional scale in order to explain the forest fires behaviour in the three bioclimatic regions where the Iberian Peninsula is included. In addition, this study evaluates the potentiality of the Normalized Vegetation Water Index (NDWI) in forest fire potential determination. MODIS spectral range covers the short wave infrared (SWIR), necessary for NDWI calculation (Barbosa et al., 2001). In addition, MODIS spectral bandwidths are finer and avoid the water absorption regions in the NIR (Huete et al., 1996). Thus, this instrument seems to be appropriate to study forest fire potential.

Study Area

The study region is the Navarra Autonomic Community, situated in the North-West part of the Iberian Peninsula and with a surface of 10.420 Km^2. This region can be divided in three bioclimatic areas: Mediterranean, Atlantic and Alpine. Climatic conditions within each region are similar enough to dictate similar characteristics of soil and potential climax vegetation; hence, they show distinct forest fire behaviour.

The Atlantic and Alpine regions are located in the Northern area. This is a mountainous area with high slopes and 2000 meter average elevation and where precipitation can be as high as 1600 mm per year. The Atlantic region is characterized mainly by a warm marine climate, strongly influenced by the sea, with abundant rains, fog and drizzles and without extreme temperatures. In the alpine region two sub regions can be distinguished: one characterized by a continental climate and other sub region close to Mediterranean area which represent a transition zone between cold and warm Mediterranean climate. The Mediterranean area is located in the southern part of Navarra, average elevation is 300 meters and precipitation can be less than 400 mm. The climate is Mediterranean, with a clear Atlantic influence in its Western part and a greater influence of continental climate towards the East.

Deciduous forest predominates in Atlantic, coniferous in Alpine and sclerophyllous oak forest in Mediterranean region. In the Atlantic region fires are frequent and generally small. Occurrence is characterized by a bi-modal pattern with two maximums one at the beginning of the spring, and another one in autumn. Intermediate fire frequency with a higher relative incidence of medium and large fires is common in Mediterranean region. In this area the forest fire patterns show an absolute maximum in summer. In the Alpine region the forest fires behaviour is characterized by a low fire frequency and a strongly seasonal and annual variability.

Methodology

This study deals with forest fire potential which can be defined as a measure, scaled from 0 to 100, of the fuel sources available for burning (Chuvieco et al., 1989).

The inputs of the model are: extinction moisture, ten-hour timelag dead fuel moisture and vegetation content percentage. The output of the model is a regional forest fire potential index at 500 meters of spatial resolution. The index is updated every eight days.

Model definition

FPI estimates vegetation susceptibility to ignition, however does not take into account the probability of an ignition source. The FPI is defined in the equation 1 (Burgan et al., 1998; Sebastián and San Miguel-Ayanz, 2001):

$$FPI = 100 \times \left(1 - FMC10HR_{FRAC}\right) \times \left(1 - VC\right), \quad \text{[Eq.1]}$$

where $FMC10HR_{FRAC}$ [%] is the ratio between ten-hour-timelag dead fine fuel moisture (FMC10HR) [%] (Forsberg and Deeming 1971) and the extinction moisture content (H.EXT) [%]. VC [%] is the vegetation content percentage, which depends on the maximum percentage of live vegetation (VC_{MAX}) [%] and the relative greenness (RG) [%].

Ratio between dead fuel moisture content and extinction moisture

The dead fine fuel takes ten hours to lose 63% of the difference in moisture between its initial content and the equilibrium moisture with the atmosphere, supposed constant the temperature and the atmospheric moisture (Chuvieco et al, 2004). This fuel corresponds with small branches of diameter between 0.6 and 2.5 cm (Anderson, 1985). The dead fine fuel moisture depends on atmospheric moisture. According to Forberg (1927) the moisture of the dead fine fuel constantly tends to reach the value of the atmospheric equilibrium moisture, which is changing continuously. Thus, the humidity of the fine and dead fuel is calculated according to the equation 2.

$$FMC10HR = 1.28 \times EMC \quad \text{[Eq.2]}$$

Where EMC [%] is the equilibrium moisture content.

The equilibrium moisture is unique for each combination of temperature and relative moisture. The algorithms used are the ones develop by Fosberg et al. (1971) (Eqs. 3, 4 and 5).

$$EMC = 2.22749 + 0.160107 \times H - 0.014784 \times T \quad \text{if } 10\% \le \text{H} \le 50\% \quad \text{[Eq.3]}$$

$$EMC = 21.0606 + 0.005565 \times H^2 - 0.00035 \times H \times T - 0.483199 \times H \quad \text{if H} \ge 50\% \quad \text{[Eq.4]}$$

$$EMC = 0.03229 + 0.281073 \times H - 0.000578 \times H \times T \quad \text{if H} \le 10\% \quad \text{[Eq.5]}$$

Where H [%] and T [ºC] are the relative moisture and the air temperature respectively (Forsberg and Deeming 1971).

Daily maximum temperature (T) and minimum relative moisture (H) acquired from thirty four meteorological stations distributed in the study region were used in this work. Spatial interpolation of maximum temperature and minimum relative moisture was carried out. Regression Kriging using the elevation as auxiliary variable was applied to temperature (Hengl et al., 2004), and linear regression was used for minimum relative moisture using the latitude, temperature and elevation as independent variables.

Dead fuel moisture was limited by the extinction moisture. The extinction moisture is defined as the dead fuel moisture at which a fire will not spread (Rothermel 1972), and it is a constant value for each fuel type. This variable was derived from the fuel type map provided by the Spanish Ministry of Environment.

Live vegetation content percentage

The study period covers from February 2000 to December 2005, thus the time series is composed by two hundred and sixty nine 8-day composites MODIS surface-reflectance products (MOD09) (i.e.) provided by the NASA Distributed Active Archive Centre in an HDF-EOS format. The MODIS reprojection tool (http://edc.usgs.gov/programs/sddm/modisdist/) was used to merge the four tiles that cover the Iberian Peninsula re-project UTM zone 30.

Relative greenness (Eqs. 6 and 7) (RG_{NDVI} and RG_{NDWI}) (Burgan and Hartford, 1993) were derived from both, NDVI (Normalized Differenced Vegetation Index) (Rouse et al., 1973) and NDWI (Normalized Vegetation Water Index) (Gao, 1996). RG is used as a proxy to estimate the percentage of vegetation content that is alive and to indicate live moisture.

$$RG_{NDVI} = \left(\frac{NDVI - NDVI_{MIN}}{NDVI_{MAX} - NDVI_{MIN}} \right) \times 100 \quad \text{[Eq.6]}$$

$$RG_{NDVI} = \left(\frac{NDWI - NDWI_{MIN}}{NDWI_{MAX} - NDWI_{MIN}} \right) \times 100 \quad \text{[Eq.7]}$$

Where $NDVI_{MAX}$ ($NDWI_{MAX}$) and $NDVI_{MIN}$ ($NDWI_{MIN}$) represent the maximum and minimum temporal value of NDVI (NDWI) for a pixel during the study period respectively.

Live vegetation content percentage (Eqs. 8) is estimated as the product of the maximum percentage of live vegetation in each pixel during the study period (VC_{MAX}) and the relative greenness (Burgan and Hartford 1993).

$$VC = VC_{MAX} \times RG \qquad \text{[Eq.8]}$$

Where VC is the vegetation content percentage and VC_{MAX} and RG are the maximum percentage of live vegetation and the relative greenness respectively.

The algorithm used to calculate the maximum percentage of live vegetation is the one of the following (Eqs. 9 and 10) depending on which vegetation index is used:

$$VC_{MAX} = 0.25 + 0.50 \times \left(\frac{NDVI_{MAX}}{NDVI_{ABSOLUTE-MAX}} \right), \qquad \text{[Eq.9]}$$

$$VC_{MAX} = 0.25 + 0.50 \times \left(\frac{NDWI_{MAX}}{NDWI_{ABSOLUTE-MAX}} \right), \qquad \text{[Eq.10]}$$

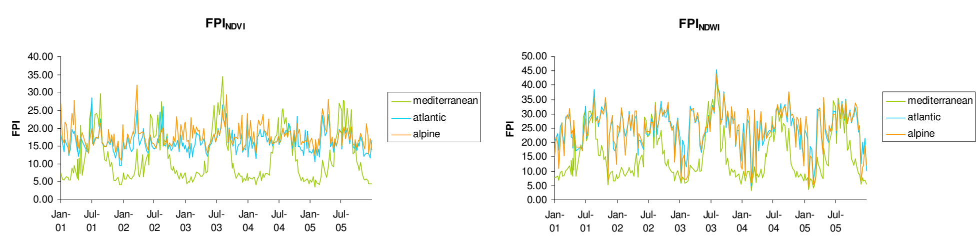
where VC_{MAX} is a constant for each pixel based on the maximum NDVI or NDWI in a given location during the study period and the overall maximum NDVI or NDWI in any location in the study area during the same period.

Evaluation method

Forest fire statistics were obtained from SITNA (Sistema de Información Territorial de Navarra). The evaluation process was carried out by comparing the monthly forest fires with the FPIs (i.e. FPI_{NDVI} and FPI_{NDWI}) monthly average values in each bioclimatic region from 2002 to 2004.

Results and discussion

Figures 1.a, b show the temporal variation of FPI_{NDVI} and FPI_{NDWI} by bioclimatic region.

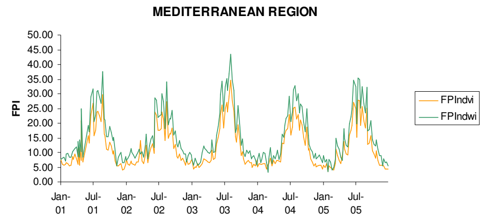


a) b)

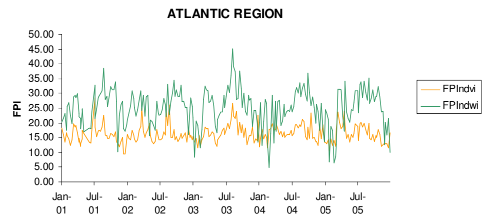
Figure 1— Temporal variation of a) FPI_{NDVI} and b) FPI_{NDW}I in Mediterranean (green), Atlantic (blue) and Alpine (orange) regions.

FPI_{NDVI} shows small seasonal fluctuations in Alpine and Atlantic regions and a distinct seasonal pattern in the Mediterranean region. On the other hand FPI_{NDWI} shows a bi-modal pattern in both, the Atlantic and Alpine regions with peaks in spring and autumn.

Figures 2.a, b, c show the temporal variation of both FPIs in Mediterranean, Atlantic and Alpine bioclimatic regions respectively.



a)



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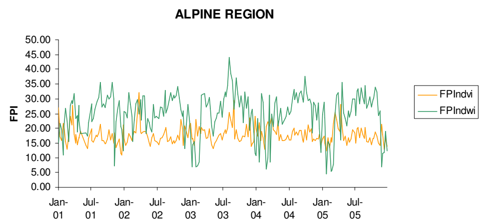


c)

Figure 2— Temporal variation of FPI_{NDVI} and FPI_{NDWI} in a) Mediterranean region, b) Atlantic region and c) Alpine region.

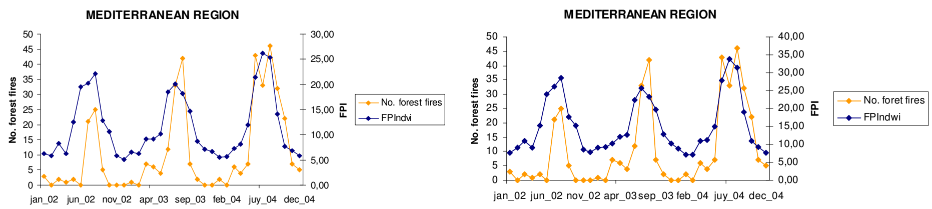
In the Mediterranean region FPI_{NDVI} and FPI_{NDWI} follow similar patterns with FPI_{NDWI} showing slightly higher values. Time series show a uni-modal trend with a significant peak in summer, typical of this region (Velez, 2000). The forest fires potential is found low during the growing period, due to the full live vegetation cover, and high during the dry period. The dominant vegetation in this region which is grasses shows a fast response to moisture, explaining the high correlation found between FPI_{NDVI} and $FPI_{NDWI.}$

On the other hand, the bi-modal pattern (i.e. with two maximum values, at the end of the summer and at the beginning of the spring) of the Atlantic regions is captured only by FPI_{NDWI}. FPI_{NDVI} remains close to stable during the year with a smooth increase of the forest fire potential in spring. In the Alpine region the trend of both indexes are similar to Atlantic region.

This difference between FPI_{NDWI} and FPI_{NDVI} in the Atlantic region may be due to the different response of NDVI and NDWI to moisture variability in deciduous forest. While NDVI responds to structural and pigment variability, probably NDWI is more sensitive to subtle moisture changes. Since deciduous forest response to the lack of moisture more slowly than grasslands, NDWI can show a response at the first stages of moisture stress before structure and pigments are affected.

In the Iberian Peninsula, there is a relationship between the potential vegetation type and forest fire characteristics. A high fire frequency and a low proportion of affected surface usually are associated to Atlantic climates where the deciduous forests predominate. Forest fires with intermediate frequencies and affected surfaces of medium to large correspond to sclerophyllous oak forests. While, coniferous forest has a low frequency of forest fire with an irregular seasonal and annual variability (Vázquez et al., 2002).

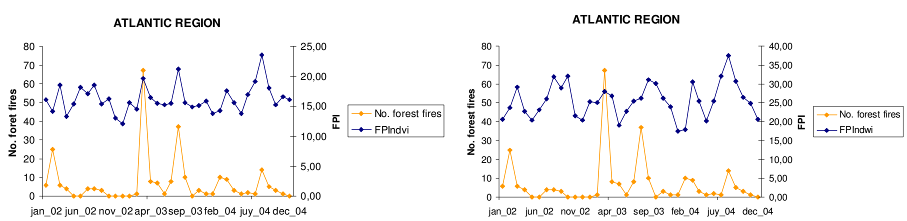
The comparison between monthly average FPI values and monthly sum of number of fires during 2002, 2003, and 2004, in Mediterranean, Atlantic and Alpine bioclimatic region respectively are presented in the figures 3.a, b, 4.a, b, 5.a and 5.b.



a) b)

Figure 3— Comparison between number of forest fires and a) FPI_{NDVI} and b) FPI_{NDWI} in the Mediterranean region.

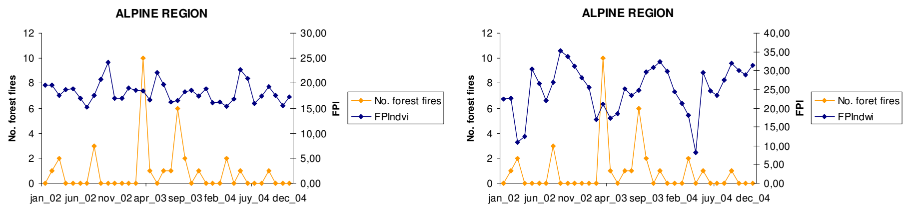
There is a high correlation between the number of fires and forest fire potential using both indexes. FPI values peaks coincide with forest fire peak events. The largest number of fires is presented in the year 2004, as well the highest FPI values. In this region the correlation found between number of fires and forest fire potential is higher than between affected surface and forest fire potential, due to the low relationship between frequency and affected surface characteristic of this region (Vazquez et al., 2002).



a) b)

Figure 4— Comparison between number of forest fires and a) FPI_{NDVI} and b) FPI_{NDWI} in the Atlantic region.

As previously mentioned, forest fire behaviour is characterized by a bi-modal pattern with two maximum values in spring and autumn. Usually it is assumed that this bi-modal pattern is due to human reasons. However, the high correlation between forest fire event and FPI_{NDWI}, which does not take into account this human inference, indicates the presence of some environmental factors such as the amount of dead fuel in autumn or the wind drying effects in spring, affecting this behaviour and that NDWI captures. Although FPI_{NDVI} detects the fire forest event, it does not capture such trend the bi-modal trend. The relationship between forest fire potential and affected surface is similar to the correlation found between forest fire potential and the number of forest fires. This is explained by the high correlation between surface and frequency characteristic of this region (Vazquez et al., 2002).



a) b)

Figure 5— Comparison between number of forest fires and a) FPI_{NDVI} and b) FPI_{NDWI} in the Alpine region.

There is not any relationship between the number of fires and the forest fire potential in this region. It could be due to the specifics characteristics of the mountain where the behaviour and the seasonal and inter-annual variation of forest fires are irregular. In addition, the effects of snow and cloud could distort the results.

The figures 6 and 7 show the seasonal spatial distribution of forest fire potential during the year 2003.

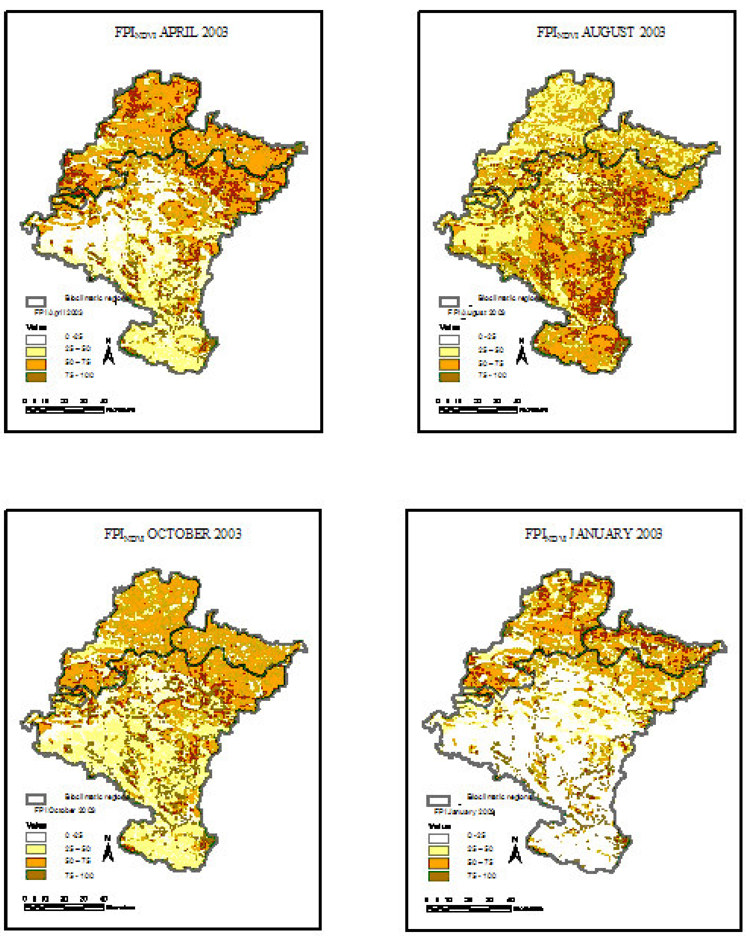


Figure 6— Seasonal spatial variation of FPI_{NDVI} during the year 2003.

The forest fire potential in Atlantic and Alpine region is always higher than in the Mediterranean region except during summer. In spring the forest fire potential is found to be high and uniform in the Alpine and Atlantic regions, however in autumn this forest fire potential is centred where the dominant fuel type is forest litter which has high extinction moisture.

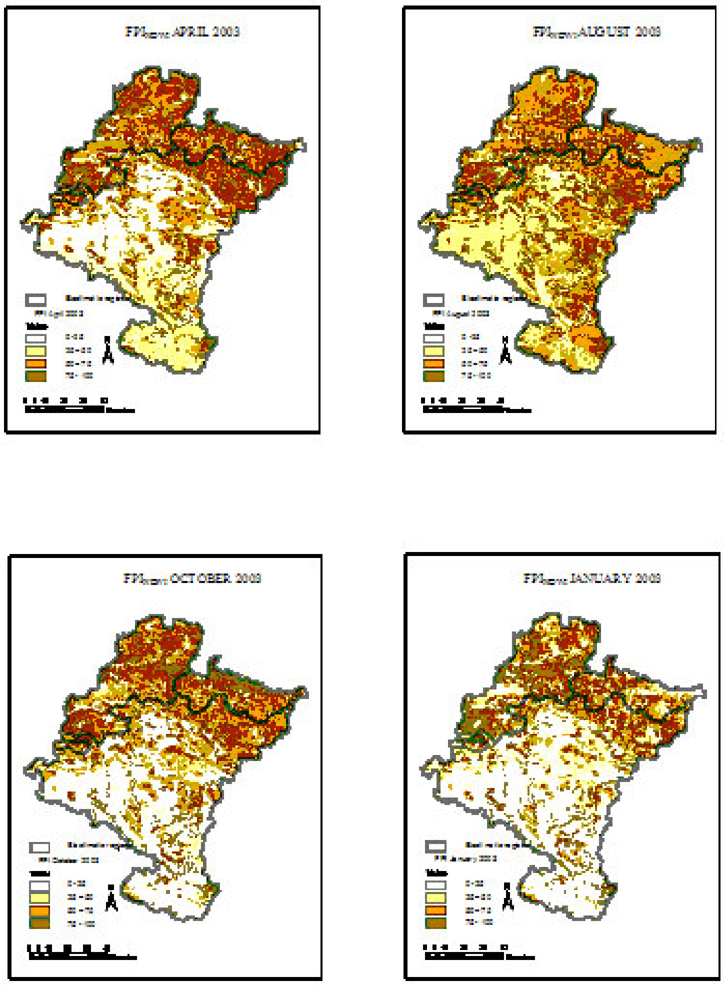


Figure 7— Seasonal spatial variation of FPI_{NDWI} during the year 2003.

Forest fire potential estimated by FPI_{NDWI} shows higher values in Atlantic and Alpine region during the whole year as opposite to FPI_{NDVI} estimations. Two significant maximum values can be appreciated in Atlantic region in spring and in autumn and a relative maximum in summer which agrees with the bi-modal behaviour of forest fires in this region. The highest forest fire potential areas in the Atlantic and Alpine regions in autumn are those where the dominant fuel type is forest litter. An absolute maximum value in summer is found in the Mediterranean region, which describe the uni-modal behaviour of forest fires in this region.

Conclusion

This study presents a methodology to forest fire potential estimation at a regional scale. The output of the model is updated each eight days from February 2000 to December 2005, it has 500 meters spatial resolution and the index is scaled from 1 to 100.

In the Mediterranean region both FPIs explain the uni-modal behaviour of forest fires typical of this area. In addition, both show a good correlation between forest fire potential values and fires occurrence (number of fires). In the Atlantic region they show differences so that only FPI_{NDWI} describe the bi-modal behaviour of forest fires showing a positive correlation with the number of fires as well. Thus, The results of this study indicate that FPI_{NDWI} can provide a useful index of forest fire potential variability on seasonal time-scale in the Atlantic region. Hence, this indicates that NDWI, delivered from MODIS satellite images, is a useful vegetation index to estimate to forest fire potential in Atlantic region.

In general terms, the forest fire potential in Atlantic and Alpine regions presents higher values than the forest fire potential in Mediterranean region due to the importance of the vegetation content percentage in the model. Frequency distribution of FPI values was very similar for all years of the study period thus the fire occurrence and the FPI remains relatively constant. This is an important fact in forest fires potential prediction. Predict forest fire potential areas in the future can help to design regional or national fire defence plans. Although FPI_{NDVI} can detect forest fire event in Atlantic region, however, a bi-modal trend is not evident. Hence, forest fire potential behaviour is less predictable using this index. Nevertheless, FPI_{NDWI} shows a better correlation between forest fire potential and forest fire event as well as shows a bi-modal behaviour.

Fire regimes can be used to understand the past role of fire, current changes in fire regimes due to management actions, and as indicators to future management practices and policies. Such dynamic variability of forest fire potential can have significant implications for defining management strategies (Velez, 2000). The difference found in the spatial and temporal dynamic of forest fire potential in the three regions depends on the model used. This fact can be important in terms of management's implications. For instance, in summer FPI_{NDVI} present the higher forest fire potential areas in Mediterranean region while these higher potential areas are presented in Alpine and Atlantic regions using FPI_{NDWI}.

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