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FOREST FIRE POTENTIAL INDEX FOR NAVARRA AUTONOMIC COMMUNITY (SPAIN)

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Forest Fire Potential Index for Navarra Autonomic Community (Spain)

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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.

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1 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.

Almost one hundred and eighty thousand hectares were burned during 2005 (MIMAM 2006a) (Fernandez et al., 1997; Gonzalez –Alonso et al., 1997; San Miguel et al., 2001). In Spain it is recognized that forest fires are one of the main environmental problems, therefore, forest fire potential estimation is one of the main concerns of the Spanish Environmental Administration. Identifying areas of high forest fire potential and understanding how it changes over time is essential for prioritizing forest management activities and reduces damage (Pyne et al., 1996). Thus, it is essential to develop methodologies and strategies to identify and assess areas of high forest fire potential.

Estimating forest fire potential requires evaluating both, biotic factors, such as fuel type and abiotic factors, such as climate (Burgan et al., 1998). 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). Regarding the time-scale of variation the indexes can be classified into long-term indexes (structural) (Etxeberria et al., 2002, Chuvieco and Congalton, 1989, Abarca and Quiroz, 2005) and short-term indexes (dynamic) (Chuvieco and Salas, 1996, Aguado et al., 2003, Dasgupta et al., 2006). The first ones are based on variables that change relatively little in the short to medium term (e.g. vegetation structure) while dynamic indexes are based on variables that change nearly continuously (e.g. fuel moisture). Both types of variables have a strong influence on the ignition and the propagation of fire (Chuvieco et al., 2004).

Most of the indexes designed are based either on meteorological data or on remote sensing information; however, few studies use the combination of both. Generally meteorological indexes supply information of dead fuel moisture (Viegas et al., 2001; Aguado et al., 2003), and remote sensing data provide information about live vegetation.

The use of remote sensing methods provides temporal and spatial coverage without costly and intense fieldwork. Also, integration of spatial data in Geographic Information Systems (GIS) allows storing and processing large volumes of spatial data (Chuvieco et al., 1996) as well as carrying out spatial analysis (Sunar and Özkan, 2001). Remote sensing techniques have been widely used for burned area mapping on both local and global scale (Chuvieco et al., 2003; Riaño et al., 200, Pereira et al., 1999). However, fewer studies have been done regarding the possibility of fire ignition (Chuvieco et al., 2003).

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. Low NDVI values mean dry vegetation or soil whereas high values indicate maximum greenness (Cohen, 1991). 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., 1999, Chuvieco et al., 2003). Thus, vegetation greenness provides a useful parameterization of the vegetation moisture content (Burgan et al., 1998).

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). For instance, Chuvieco et al., (2002) designed an index to estimate grass and shrubs water content using NDVI and the AVHRR-NOAA thermal bands oriented to forest fire risk assessment. Later they improved it taking into account the relative greenness index and the day of the year (Chuvieco et al., 2003; Chuvieco et al., 2004).

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). Jackson et al., (2004) compared NDVI and NDWI fuel moisture estimation and found that NDWI yield better results than NDVI. Maki et al., (2004) developed a vegetation dryness index to estimate vegetation moisture content using NDWI; the results show a positive relation between NDWI and live vegetation moisture content.

The Moderate Resolution Imaging Spectroradiometer (MODIS) sensor on the TERRA satellite has seven bands in the optical domain (B, G, R, NIR, SWIR1, SWIR2, and SWIR3) that are measured at 500m resolution which 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). Zarco-Tejada et al (2003) and Hao et al. (2002) studies demonstrated the potential applicability of MODIS data for water content estimation, based on NDVI, NDWI and surface temperature (Zarco Tejada et al., 2003, Hao et al., 2002).

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). This means (Forberg, 1927) that the moisture of the dead fine fuels tends to reach equilibrium with atmospheric moisture, which is in constant variation. Consequently, during the night the dead fuel must absorb moisture whereas during the day happens just the opposite.

Thus, most models to estimate dead fuel moisture are based on meteorological variables (Viney et al., 1990; Forberg and Deeming 1971; Burgan et al., 1998; Sebastián and San Miguel-Ayanz, 2001).

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). As previously mentioned, meteorological indexes only take into account the characteristic of the climate which is related to dead fuel conditions while remote sensing data provide information about live vegetation. Combining both types of information increase the robustness of the indexes which allows a better understanding of the phenomenon.

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.

1.1 Research objectives and research questions

The main objective of this work is to design an operative forest fire potential index at a regional scale. 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 water status (Burgan et al., 1998; Sebastián and San Miguel-Ayanz, 2001). In addition, this research investigates the suitability of NDWI vegetation index derived from MODIS satellite images, in order to assess forest fire potential with higher accuracy. Finally this study shows the spatial and temporal variability of the forest fire potential in each bioclimatic region of Navarra Autonomic Community.

Section one (Introduction) describes a general introduction to the topic selected as well as the problem definition, followed by the relevant background concerning the topics and the objectives. Section two and three (Study area and methodology) describes the study area and the used data and explains which techniques are used to fulfil the goals. This methodology is divided into pre-processing of remote sensing and meteorological data and the FPI components calculation. In addition, the inputs and algorithm of the FPI are presented. The fourth section (Results and discussion) presents an overview of the results and the analysis and gives the discussion pertinent for understanding the results. The fifth section (Conclusions) summarizes the main conclusions as derived from this study and gives some improvements for future researches in this field.

2 STUDY AREA

The study region is 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 annual averages of temperature and precipitation of each bioclimatic region are shown in table 1.

Table 1. Annual average of temperature and precipitation in Atlantic, Alpine and Mediterranean region.

Bioclimatic region	**Annual average temperature (ºC)**	**Annual average precipitation (mm)**
Atlantic	8,5 – 14,5	1.100 – 2.500
Alpine	7,0 – 13,0	700 – 2.200
Mediterranean	11,0 – 14,0	450 – 1.100

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. Figure 1 shows the situation of Navarra.

Figure 1. Location of study area

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.

3 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). Thus, the FPI measures the susceptibility of the vegetation to ignition. As such, it does not account the probability of the ignition events.

The inputs of the model are: extinction moisture delivered from fuel type map, ten-hour timelag dead fuel moisture calculated from meteorological data (maximum temperature and minimum relative moisture) and vegetation content percentage obtained from RG vegetation index delivered from MODIS satellite images.

The output of the model is a regional forest fire potential index at 500 meters of spatial resolution with FPI values on a scale from 1 to 100. The index is updated every eight days. Figure 2 shows the conceptual model followed in this work.

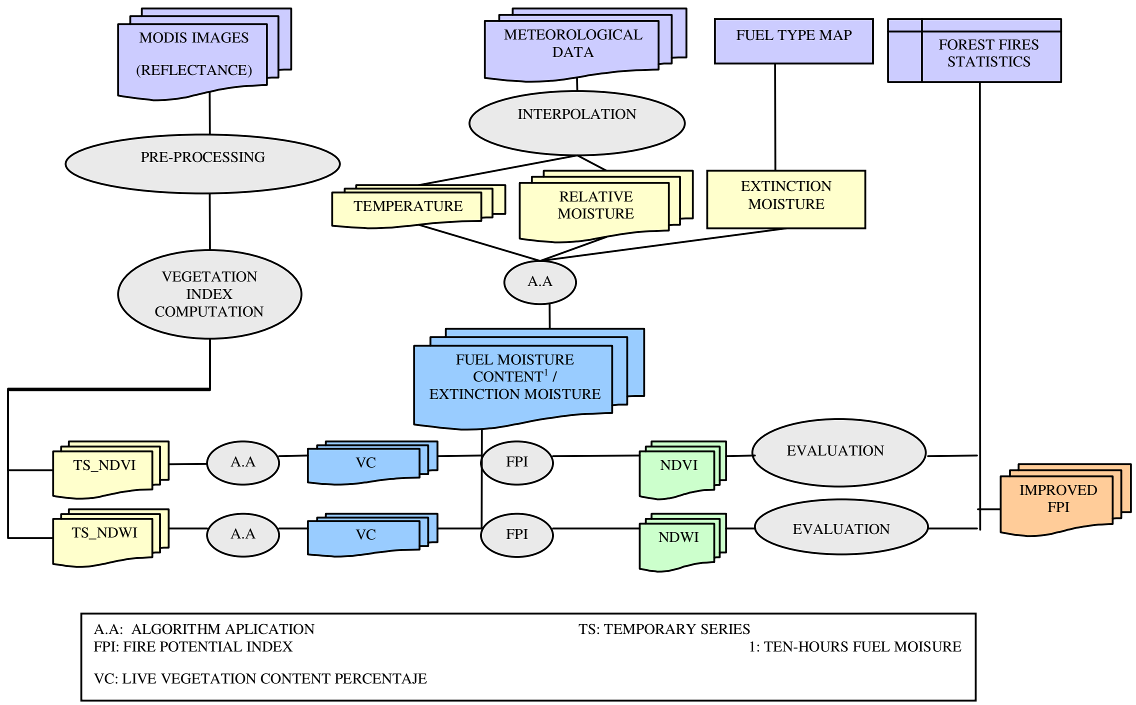


Figure 2. Conceptual model of FPI assessment. The index is based on both remote sensing images and meteorological data. The parallel path at the bottom shows that the analysis involved a comparison between the NDVI and NDWI indexes.

3.1 Remote sensing data pre-processing

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 (MODIS Products, 2006). The MODIS reprojection tool (MODIS Reprojection tool, 2006) was used to merge the four tiles that cover the Iberian Peninsula re-project UTM zone 30.

MODIS images are composed by seven atmospherically corrected bands in the optical range with band centers at 648 nm, 858 nm, 470 nm, 555 nm, 1240 nm, 1640 nm, and 2130 nm. The spatial resolution is approximately 500 meters. For each date the seven bands were extracted and time series for each band were compiled.

NDVI and NDWI were compute for each date and also a time series of each index was constructed. NDVI (Normalized Differenced Vegetation Index) (Rouse et al., 1973), is a normalized difference between Near Infrared and Red channels, whereas, NDWI (Normalized Vegetation Water Index) (Gao, 1996), is a normalized difference between Near Infrared and SWIR1 (Short Wave Infrared Radiometer) channels.

Relative greenness (Eqs. 1 and 2) (RG_{NDVI} and RG_{NDWI}) (Burgan and Hartford, 1993) were derived from both, NDVI and NDWI. Relative greenness algorithm takes into account the range of temporal variability of a specific pixel and normalizes the index value respect to the highest and lowest occurring values during the study period. This procedure allows estimating the evolution of forest fire potential for the specific condition of that pixel.

In our algorithm RG is used as a proxy to estimate the percentage of vegetation content that is alive and to indicate live moisture.

$$RG_{NDVI} = \left(\frac{NDVI - NDVI_{MIN}}{NDVI_{MAX} - NDVI_{MIN}} \right) \times 100 \qquad \text{[Eq.1]}$$

$$RG_{NDWI} = \left(\frac{NDWI - NDWI_{MIN}}{NDWI_{MAX} - NDWI_{MIN}} \right) \times 100 \qquad \text{[Eq.2]}$$

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.

3.2 Meteorological data processing

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. In order to avoid working with anomalous and no representative values aggregation to eight day periods was done by calculating the mean.

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. These interpolation methods are relatively simple which contributes to the functionality of the index; still it is expected that will provide higher accuracy than the one used by Burgan (inverse distance weight).

The linear regression equation used to interpolate the minimum relative moisture (H) is represented by the equation 3:

$$H = -107.90 - 1.434 \times T + 3.8761 \cdot 10^{-5} \times L + 0.0010 \times A \qquad (r^2 = 0.79), \qquad \text{[Eq.3]}$$

where T is temperature [^{o}C], L latitude [m] and A is elevation [m].

3.3 Model definition

FPI estimates vegetation susceptibility to ignition, however does not take into account the probability of an ignition source. The inputs of the model are: extinction moisture, dead fuel moisture and vegetation content percentage. The output of the model is a regional forest fire potential index updated each eight days and with 500 meters spatial resolution and scaled from 1 to 100. The FPI is defined in the equation 4 (Burgan et al., 1998; Sebastián and San Miguel-Ayanz, 2001):

$$FPI = 100 \times (1 - FMC10HR_{FRAC}) \times (1 - VC), \qquad \text{[Eq.4]}$$

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) [%].

3.4 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. During the night the equilibrium moisture is greater than the dead fine fuel moisture, hence, the dead fuel must absorb moisture whereas during the day it happens just the opposite. Since the forest fire potential index takes into account maximum temperatures and these are reached during the day, we are in the second situation in which the dead fine fuel moisture is higher to the equilibrium moisture, approximately 1.28 times larger. Thus, the humidity of the fine and dead fuel is calculated according to the equation 5:

$$FMC10HR = 1.28 \times EMC \, , \qquad \text{[Eq.5]}$$

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. 6, 7 and 8).

$$EMC = 2.22749 + 0.160107 \times H - 0.014784 \times T \qquad \text{if } 10\% \leq \text{H} \leq 50\% \text{ [Eq.6]}$$

$$EMC = 21.0606 + 0.005565 \times H^2 - 0.00035 \times H \times T - 0.483199 \times H \qquad \text{if H} \geq 50\% \text{ [Eq.7]}$$

$$EMC = 0.03229 + 0.281073 \times H - 0.000578 \times H \times T \qquad \text{if H} \leq 10\% \text{ [Eq.8]}$$

Where H [%] and T [^{o}C] are the relative moisture and the air temperature respectively (Forsberg and Deeming 1971).

If the moisture content is very high the combustion process cannot take place. Thus, dead fuel moisture must be 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. The fuel types are defined using the former ICONA's keys (MIMAM, 2006b) which are based on the ones developed for the BEHAVE model (Burgan and Rothermel, 1984).

$$FMC10HR_{FRAC} = \frac{FMC10HR}{H.EXT} \qquad \text{[Eq.9]}$$

Where $FMC10HR_{FRAC}$ [%] is the ratio between the extinction moisture (H.EXT) [%] and the fuel moisture content (FMC10HR) [%]. It ranges from 0 to 1.

3.5 Live vegetation content percentage

The maximum percentage of live vegetation content algorithm is based on the idea that historical low values of NDVI are typical of pixels with low amount of live vegetation, due to the low level of photosynthetic activity. On the contrary, areas with historical high values of NDVI probably have a higher amount of live vegetation (Sebastián et al., 2001).

Live vegetation content percentage (Eqs. 10) 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).

$$VC = VC_{MAX} \times RG \qquad \text{[Eq.10]}$$

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. 11 and 12) depending on which vegetation index is used:

$$VC_{MAX} = 0.25 + 0.50 \times \left(\frac{NDVI_{MAX}}{NDVI_{ABSOLUTE-MAX}} \right), \qquad \text{[Eq.11]}$$

$$VC_{MAX} = 0.25 + 0.50 \times \left(\frac{NDWI_{MAX}}{NDWI_{ABSOLUTE-MAX}} \right), \qquad \text{[Eq.12]}$$

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.

In the actual FPI the vegetation content is computed using NDVI while the improved model uses NDWI which was shown to be more moisture dependent.

3.6 Evaluation method

Forest fire statistics were obtained from SITNA (Sistema de Información Territorial de Navarra). This data set is composed by the number of forest fires and the affected surface at a municipality level. The municipality that belong to more than one bioclimatic region were not use in the analysis in order to avoid data repetition.

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. The relationship between the numbers of forest fire events (fire occurrence) and forest fire potential should be higher than the relation between affected surface and fire potential due to the index does not take into account the forest fire propagation process.

4 RESULTS AND DISCUSSION

4.1 Fire potential index variables

4.1.1 Temperature and relative moisture

The thermal amplitude in the three bioclimatic regions is similar. In general, Mediterranean region presents higher temperatures, whereas Alpine and Atlantic regions show a greater inter-annual variability with respect to Mediterranean region.

Regarding the relative moisture, the amplitude and the inter-annual variability of this variable is similar in the three bioclimatic regions. In general, Mediterranean region presents lower relative moistures than Atlantic and Alpine regions.

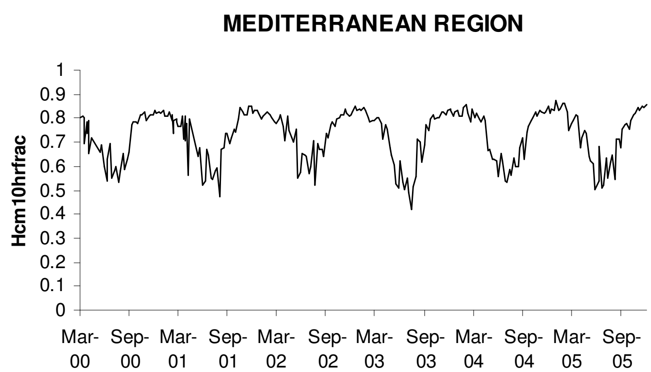
4.1.2 Vegetation indexes

NDVI and NDWI seasonal variability in the Atlantic and Alpine regions present an annual cycle with maximum values in spring, typical of natural vegetation (Volante et al., 2003). In the Atlantic region which is dominated by deciduous species both indexes increase sharply at the beginning of spring. This is due to the fact that leaf emergence in different species happens approximately at the same time. On the contrary, in fall the index decrease is more gradual because the period of leaf senescence and decay is longer and distinct for different species (Delbart et al., 2005). Alpine region present a similar pattern with a delay in the vegetation phenology. In the Mediterranean region it happens the opposite, this is due to the dominant vegetation type in this region which is grass; the indexes increase smoothly during the growing period and decrease abruptly in the mid-spring when to grasses become dry (Illera et al., 1999).

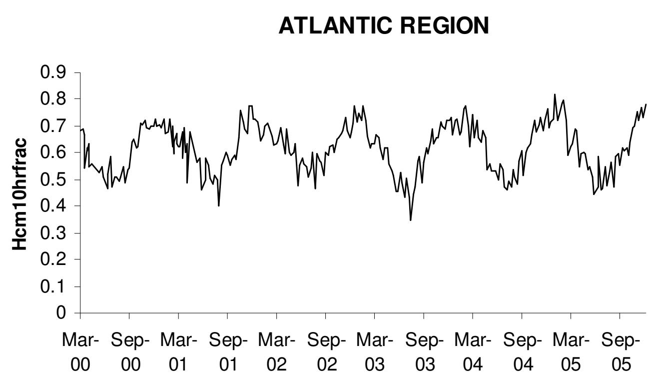
Although both indexes present a similar general pattern, NDWI shows a narrower seasonal variability respect to NDVI. The period where the amount of live vegetation is low is longer using NDWI than NDVI. This fact seems to indicate that NDWI is more sensitive to moisture than NDVI, which has been shown by other authors (Delbart et al., 2005).

4.1.3 Ratio between fuel moisture content and extinction moisture

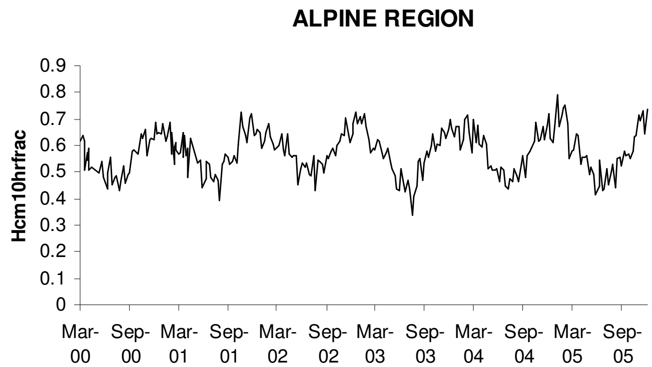
The figures 3.a, b, c show the temporal variation of the ratio between fuel moisture content and extinction moisture ($FMC10HR_{FRAC}$) for each bioclimatic region.



a)



b)



c)

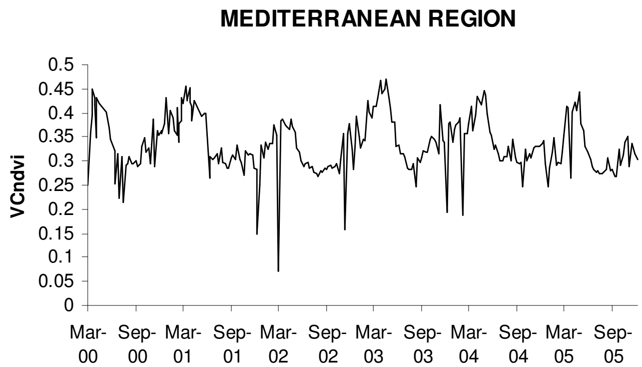
Figure 3. Temporal variation of the ratio between fuel moisture content and extinction moisture in a) Mediterranean, b) Atlantic and c) Alpine region.

$FMC10HR_{FRAC}$ starts increasing in September until it reaches its maximum value in winter. At the beginning of summer the ratio starts decreasing, this decrease continues until September. In the three bioclimatic regions the range of variation is very similar (i.e. 0.8-0.5 in Mediterranean region and 0.7-0.45 in Alpine and Atlantic region) however, this variable shows a narrower seasonal variability in Atlantic and Alpine region respect to Mediterranean region. The period where this ratio is high is longer in Mediterranean region than in Atlantic and Alpine regions.

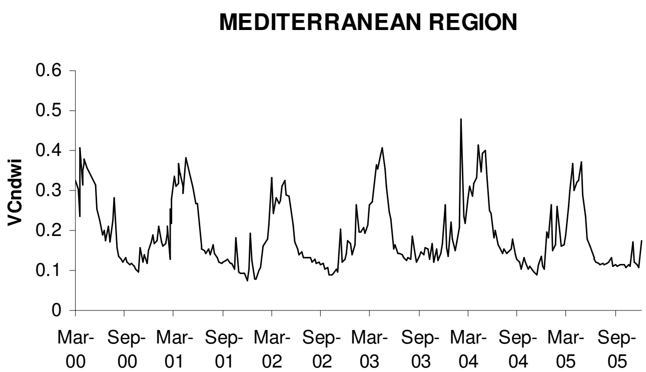
In general, $FMC10HR_{FRAC}$ shows higher values in Mediterranean region than in the other two. This difference is due to the lower extinction moisture of the fuel type in Mediterranean region. In the Atlantic and Alpine regions the fuel type dominant has higher extinction moisture thus it is necessary a great amount of moisture to avoid the fuel begins to burn so the value of $FMC10HR_{FRAC}$ is in general lower.

4.1.4 Live Vegetation content percentage

The figures 4.a, b, 5.a, b, 6.a and 6.b show the temporal variation of live vegetation content percentage using NDVI and NDWI in Mediterranean, Atlantic and Alpine regions respectively.



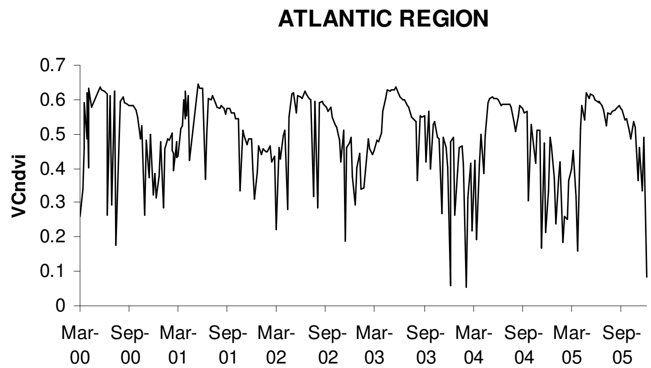
a)



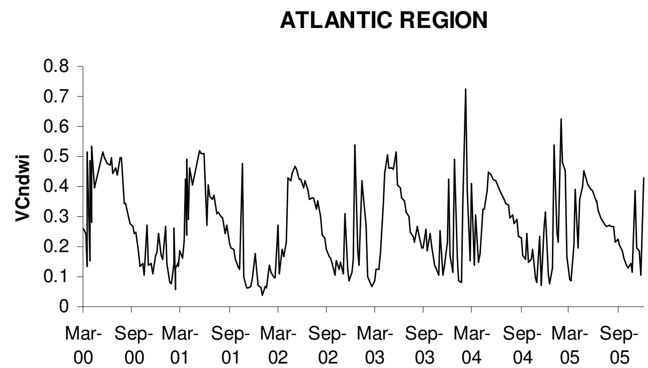
b)

Figure 4. Temporal variation of live vegetation content percentage in Mediterranean region using a) NDVI and b) NDWI.

In both cases, by mid-spring VC is decreasing sharply due to the grass fast senescence. In mid-fall VC increases smoothly as the proportion of green vegetation increases due to the first rains, this increase continues until the next spring. In general the VC_{NDVI} shows higher values than VC_{NDWI}. VC_{NDVI} shows also a smaller range of variability than VC_{NDWI} (i.e. 0.3-0.45 vs. 0.1-0.4). Also it seems that VC_{NDVI} has more noise than VC_{NDWI} probably due to the stronger effects that the atmosphere has on the VIS-NIR range of the spectrum.



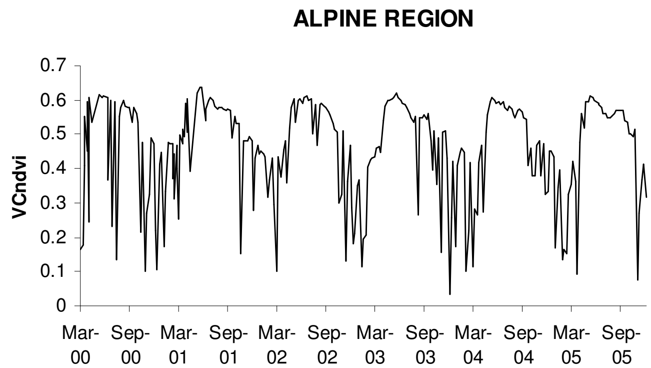
a)



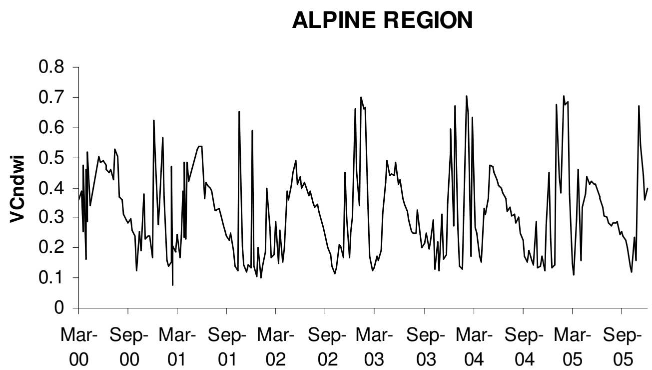
b)

Figure 5. Temporal variation of live vegetation content percentage in Atlantic region using a) NDVI and b) NDWI.

VC increases sharply at the beginning of spring due to fast leaf emergence in deciduous species, dominant in this region. By mid-summer VC starts decreasing smoothly first due to the moisture decrease and secondly leaf senescence and fall. As in the Mediterranean region VC_{NDVI} shows higher mean values and VC_{NDWI} shows a larger variability range (i.e. 0.1-0.5 vs. 0.3-0.6).



a)



b)

Figure 6. Temporal variation of live vegetation content percentage in Alpine region using a) NDVI and b) NDWI.

Alpine region present a similar pattern than Atlantic region with a delay in the vegetation phenology. VC increases sharply in mid-spring and in summer VC starts decreasing smoothly. As in the Atlantic region VC_{NDVI} shows higher mean values and VC_{NDWI} shows a larger variability range (i.e. 0.1-0.5 vs. 0.3-0.6). In addition, during the winter the noise of this variable increases in Alpine region due to the snow and clouds effects.

In general terms, the forest fire potential in Atlantic and Alpine regions present higher values than the fire potential in Mediterranean region due to the importance of the vegetation content percentage in the model. Higher biomass shows higher forest fire potential (Burgan et al., 1998); in general the amount of biomass is higher in Atlantic and Alpine than in Mediterranean region.

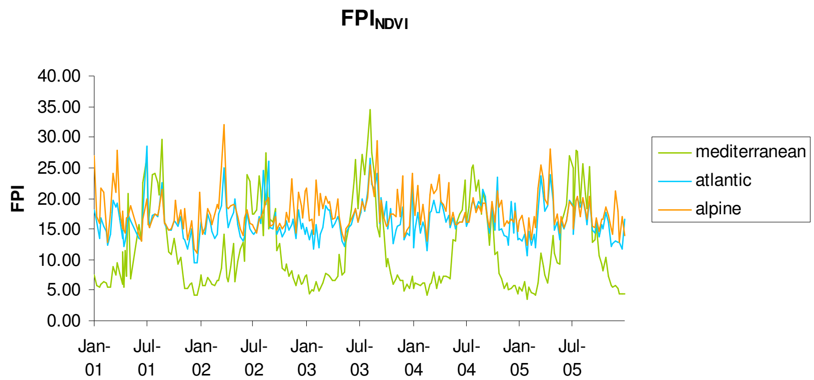
Comparing both indexes FPI_{NDWI} was found to be higher to FPI_{NDVI}. The reason could be the algorithm used to calculate the percentage of live vegetation content which depends on the VC_{MAX} factor (see equations 11 and 12).

This factor was calculated with both vegetation indexes NDVI and NDWI. NDVI has been proven to be a useful indicator of biomass (Box et al., 1989; Sannier et al., 2002); however, no such result is evident for NDWI. This could be the reason of the higher values of FPI_{NDWI} in Atlantic region with respect to Mediterranean region.

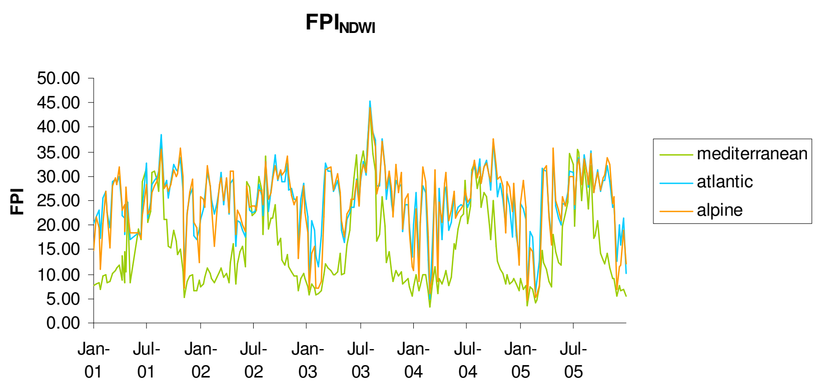
4.2 Fire Potential Index

General patterns of forest fire potential in Navarra are similar in both indexes. However, FPI_{NDWI} shows higher average values than FPI_{NDVI}. Also, FPI_{NDWI} distinguishes four seasons whereas in FPI_{NDVI} this variability is not clear, so that it discriminates only a dry and wet period. This can be due to the fact that NDWI is more sensitive to moisture than NDVI (Gao, 1996, Zarco Tejada et al., 2003, Jackson et al., 2004).

Figures 7.a, b show the temporal variation of FPI_{NDVI} and FPI_{NDWI} by bioclimatic region.



a)



b)

Figure 7. Temporal variation of a) FPI_{NDVI} and b) FPI_{NDWI} 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 8.a, b, c show the temporal variation of both FPIs in Mediterranean, Atlantic and Alpine bioclimatic regions respectively.

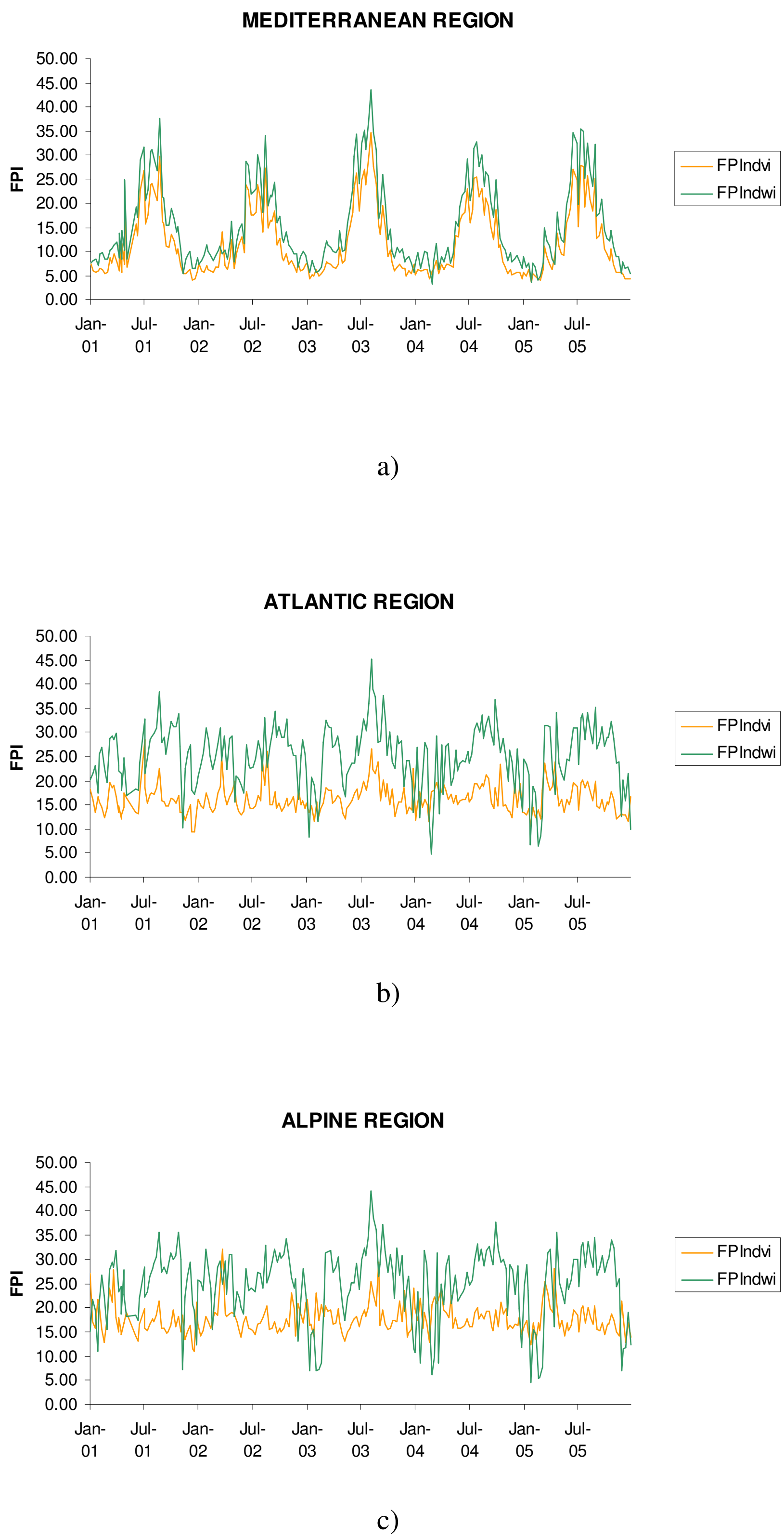


Figure 8. Temporal variation of FPI_{NDVI} and FPI_{NDWI} in a) Mediterranean region, b) Atlantic region and c) Alpine region.

In the Mediterranean region FPI_{NDVI} and FPI_{NDWI} follow similar patterns with FPI_{NDWI} showing slightly higher values. Time series show a un-imodal 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 $FPI_{NDWI.}$

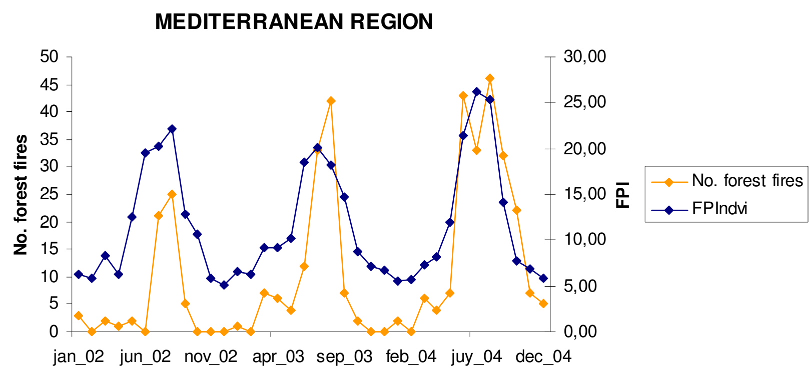
On the other hand, the bi-modal pattern (i.e. with two maximum values, at the end of the summer and at the beginning of the spring) of the Atlantic regions is captured only by FPI_{NDWI}. FPI_{NDVI} remains close to stable during the year with a smooth increase of the forest fire potential in spring.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

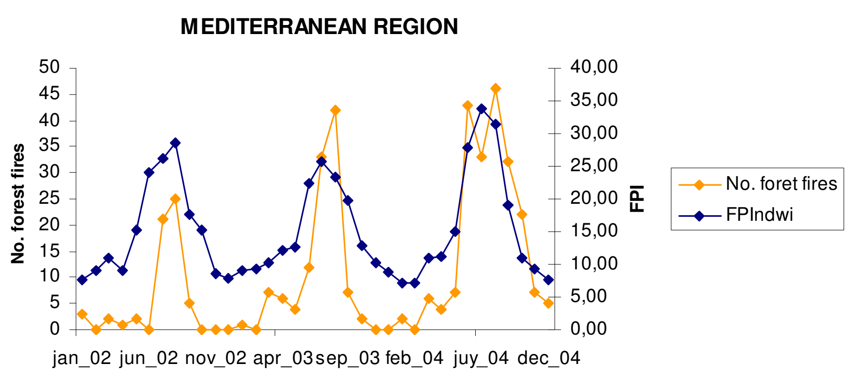
4.3 Fire Potential Index and fire statistics

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 9.a, b, 10.a, b, 11.a and 11.b.



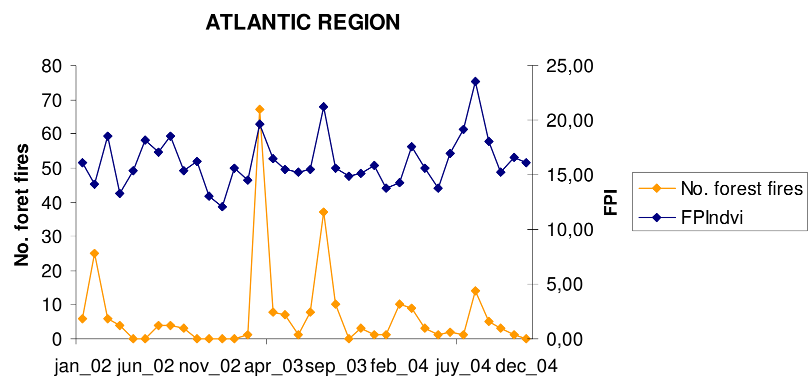
a)



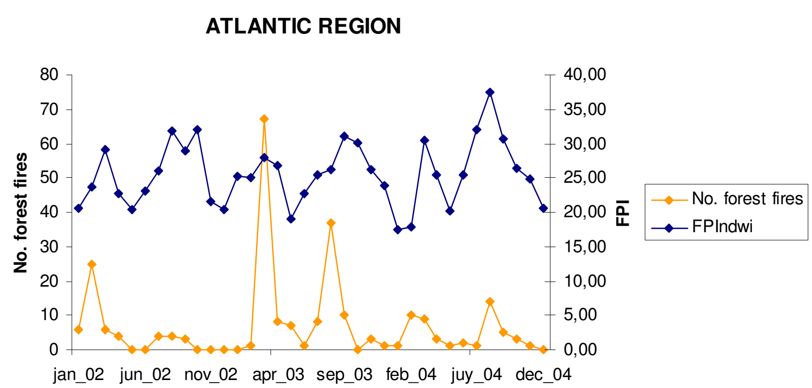
b)

Figure 9. Comparison between number of forest fires and a) FPI_{NDVI} and b) FPI_{NDWI} in the Mediterranean bioclimatic 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).



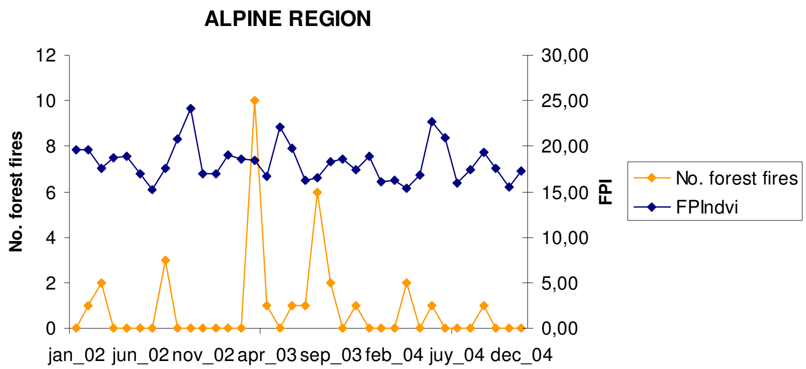
a)



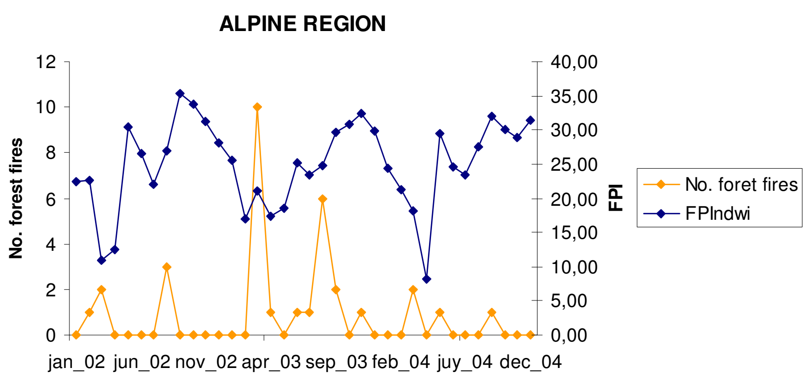
b)

Figure 10. Comparison between number of forest fires and a) FPI_{NDVI} and b) FPI_{NDWI} in the Atlantic bioclimatic 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 11. Comparison between number of forest fires and a) FPI_{NDVI} and b) FPI_{NDWI} in the Alpine bioclimatic 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 12 and 13 show the seasonal spatial distribution of forest fire potential during the year 2003.

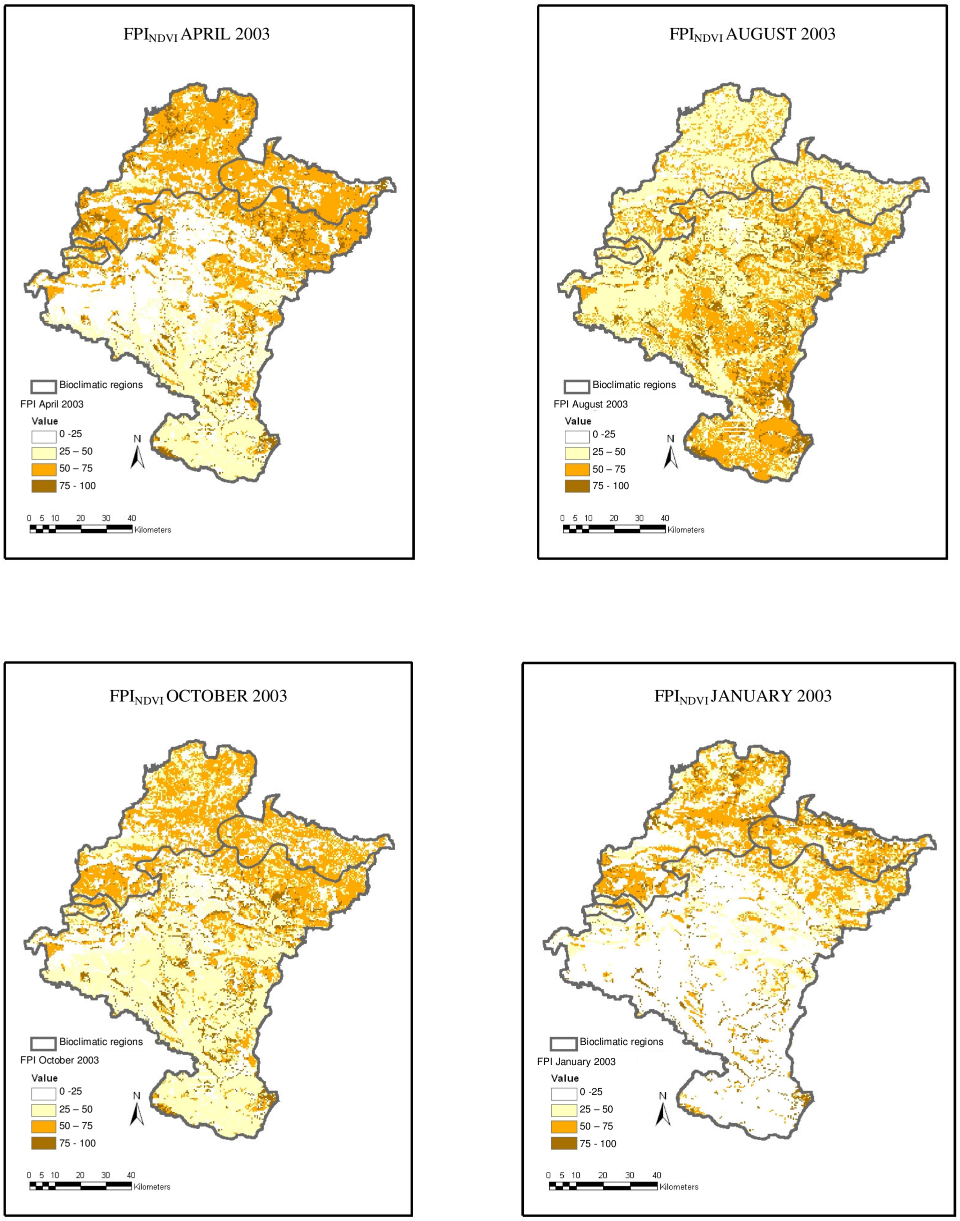


Figure 12. Seasonal spatial variation of FPI_{NDVI} during the year 2003.

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.

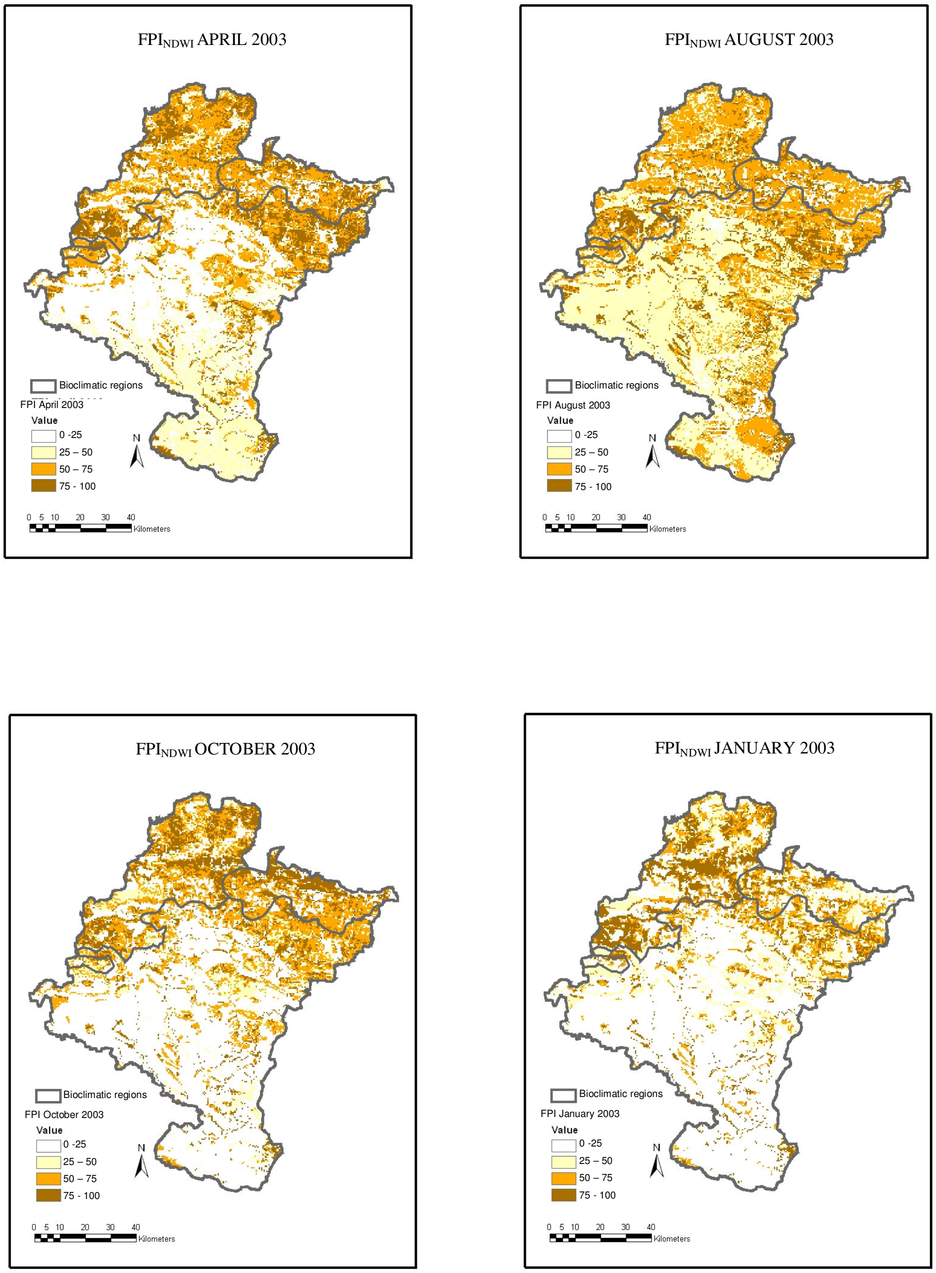


Figure 13. Seasonal spatial variation of FPI_{NDWI} during the year 2003.

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.

Considerable uniform time-series behaviour within each bioclimatic region was found each year in both FPIs (not shown here).

5 CONCLUSION

Forest fire is a complex phenomenon which is difficult to model. It is difficult to predict when it will occur. There are many variables that influence in this phenomenon; some of them are difficult to measure. Furthermore many variables are interrelated (Vélez 2000).

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.

The result of this study shows the utility of MODIS for characterizing fire potential dynamic at a regional scale and allows forest fire potential estimation in each bioclimatic region. Clouds coverage and atmospheric effects can distort the value of some pixels. However, the composite techniques based on a multistep process ensures that the date chosen is with the highest overall pixel quality during the 8-day period, that is, least atmospheric influence and the best observation geometry. It is expected that this date will be the one with highest fire potential. Another advantage of MODIS indexes computed from 500 m reflectance data is the possibility of choosing the pixel with lowest value of the blue band which allows minimizing the path radiance effect. The use of MODIS data is an improvement over AVHRR, used in the actual FPI, because of the better spatial and spectral resolution. A shift from the AVHRR to MODIS sensor involves a change from 1 Km or 4 Km to 500 m pixel resolution MODIS bands. In addition, MODIS products have more bands available covering the short wave infrared (SWIR) part of the spectrum. New sensors as MODIS-Terra or SPOT-VEGETACION are opening a new generation of forest potential indexes (Guangmeng and Mei, 2004).

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 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.

The importance of this model is that it takes into account variables which can be predicted, for instance, temperature and relative moisture can be predicted using meteorological indexes, as well as, there are models that can predict the intra-annual dynamics of plant canopies (Jolly et al., 2005), satellite observation, of seasonal changes in vegetation greenness could be useful. 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}.

5.1 Future improvements

Indicators of forest fire potential are usually developed at a local level; however, forest fire is not a local phenomenon. It would be therefore desirable to look at forest fire problem with a more ample view. In Spain there is not a consistent index at National scale, this is an important and difficult problem for which there is no standard procedure at this time. The FPI was apply at an European scale by Sebastian (2001) and in this study this model was apply at a regional scale, thus the FPI would be able to be applied to whole Spanish territory with a good spatial and temporal resolution in order to harmonize the forest fire prevention plans.

Fire statistics are usually compiled on administrative units which, commonly, do not agree with vegetation units or any other type of ecological division that reflects better climate and soil characteristics (Moreno et al. 1990, Gavilán & Fernández-González 1997). Evaluating the current role and impacts of fire on the ecosystem, and extrapolating them into the future, requires that information be converted from administrative territorial units to ecologically meaningful entities.

In other hand, this model does not address the effect of topography or the anthropogenic influence, the implementation of these variables into the model can be a subject of further works. In addition, NDWI has been proved to be a useful vegetation index in order to describe forest fire behaviour in Atlantic region, thus, futures research can explore the potentiality of another spectral vegetation indexes in forest fires potential estimation.

Finally, improvement of the interpolation process can be the topic for future works. The interpolation methods used do not take into account other factors such as proximity to the coast and separation from climatic barriers which can be relevant.

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7 APPENDIX I

Diseño de un índice dinámico de Riesgo de Incendios Forestales basado en el Fire potential Index de Burgan (RESUMEN):

El presente estudio muestra una metodología para la estimación del riesgo de incendios forestales para la Comunidad Foral de Navarra. El índice propuesto está basado en el Fire Potential Index (FPI) desarrollado por Burgan (1998) para Estados Unidos y posteriormente aplicado a Europa por Sebastián (2001). El FPI mide la susceptibilidad de la vegetación para entrar en ignición supuesta la existencia de una fuente próxima pero no evalúa la probabilidad de que dicha fuente aparezca. El FPI se compone de dos variables, la humedad del combustible fino y muerto y la carga de vegetación viva. La primera variable es estimada en función de la temperatura y la humedad relativa, obtenidas mediante un proceso de interpolación basado en la geoestadística y en la regresión lineal La carga de vegetación viva es estimada mediante el producto del RG por el máximo porcentaje de carga viva posible. Asimismo se ha estudiado la capacidad del índice de vegetación NDWI en la estimación del riesgo de incendios forestales. Los resultados muestran que tanto el FPI_{NDVI} como el FPI_{NDWI} describen el comportamiento uni-modal de los incendios en la región mediterránea. Además el FPI_{NDWI} describe el comportamiento bi-modal de los incendios de la región atlántica.

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