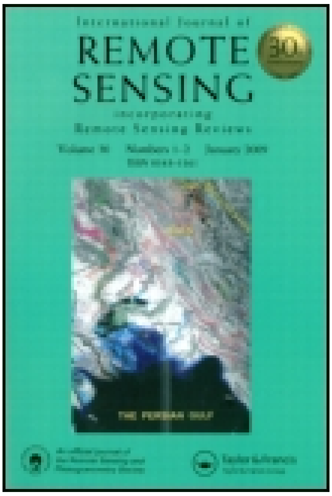


International Journal of Remote Sensing
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tres20

A comparative analysis of the use of NOAA-AVHRR NDVI and FWI data for forest fire risk assessment

A. Gabban [a] , J. San-Miguel-Ayanz [a] & D. X. Viegas [b]
[a] DG Joint Research Centre , Institute for Environment and Sustainability , TP.261, I-21020 Ispra (VA), Italy
[b] ADAI , University of Coimbra , Portugal
Published online: 20 Sep 2008.

International Journal of Remote Sensing
Vol. 29, No. 19, 10 October 2008, 5677–5687

A comparative analysis of the use of NOAA-AVHRR NDVI and FWI data for forest fire risk assessment

A. GABBAN*†, J. SAN-MIGUEL-AYANZ† and D. X. VIEGAS‡
†DG Joint Research Centre, Institute for Environment and Sustainability, TP.261, I-21020 Ispra (VA), Italy
‡ADAI, University of Coimbra, Portugal

(*Received 15 December 2005; in final form 24 December 2007*)

Fires are a major hazard to forests in the Mediterranean region, where, on average, half a million hectares of forested areas are burned every year. The assessment of fire risk is therefore at the heart of fire prevention policies in the region. The estimation of forest fire risk often involves the integration of meteorological and other fuel-related variables, leading to an index that assesses the different levels of risk. Two indices frequently used to estimate the level of fire risk are the Fire Weather Index (FWI) and the Normalized Difference Vegetation Index (NDVI). Although a correlation between the number of fires and the level of risk determined by these indices has been demonstrated in previous studies, the analyses focused on the changes in fire risk levels in areas where fires took place. The present study analyses the behaviour of the fire risk indices not only in areas where fires occurred but also in areas where fires did not take place. Specifically, the objective of this work was to compare the potential of the two indices to discriminate different levels of fire risk over large areas. Qualitative and quantitative methods were used to compare the statistical distributions of fire event frequencies with those of fire risk levels. The qualitative method highlights graphically the statistical difference between the values of the indices computed over burnt areas and the overall distribution of the values of the indices. The quantitative method, based on the use of the so-called performance index, was used to evaluate and compare numerically the potential of the indices. The analyses were performed considering very extensive datasets of fire events, satellite data and meteorological data for Spain during a 10-year period. Although the NDVI is assumed to describe the vegetation status as related to fire ignition, the results show conclusively an enhanced performance of the FWI over the NDVI in identifying areas at risk of fires.

1. Introduction

Every summer Spain is subjected to a very large number of forest fires resulting in large economic investments to manage the consequent damages. For example, in only 2003, 34% of the total number of fires in the European Mediterranean region took place in Spain, burning 149 000 hectares of wooded area and producing an estimated economic loss of 405 570 000 euros (Ministerio de Medio Ambiente 2004). Although the causes of fires in this region are generally not natural, regular measures of prevention have become necessary to reduce the amount of losses (Velez

*Corresponding author. Email: gabban@inwind.it

International Journal of Remote Sensing
ISSN 0143-1161 print/ISSN 1366-5901 online
http://www.tandf.co.uk/journals
DOI: 10.1080/01431160801958397

and Merida 2002). The evaluation of the risk of fire has been recognized as one of the most important preventive measures aimed at estimating the probability of forest fire ignition and propagation. There are several variables involved in the risk assessment. On the one hand, vegetation water stress, weather conditions and human settlements determine the probability of fire ignition. On the other hand, wind condition and landscape characteristics determine fire propagation (Pyne *et al.* 1996). The variables identified as potentially contributing to fire risk have been usually integrated into a mathematical expression (i.e. an index) that indicates the level of risk of fire. Fire risk indices are often grouped according to the variables that are used in their computation. Accordingly, they are classified into meteorological, remote sensing derived and advanced indices. Meteorological indices are those based on meteorological variables, such as wind speed or rainfall. Remote sensing derived indices make use of remote sensing data to estimate vegetation conditions in relation to photosynthetic activity or drought conditions. Finally, advanced indices are those that make use of both meteorological and remote sensing information (San-Miguel-Ayanz 2002).

In this work, two different indices extensively used in the field of forest fire risk analysis were considered and evaluated. These are the Canadian Forest Fire Weather Index (FWI) and the Normalized Difference Vegetation Index (NDVI).

First issued in 1970 (Canadian Forestry Service 1970), the FWI is made up of different components providing information about fuel moisture, rate of fire spread, fuel consumption and fire intensity. Each component is determined on the basis of information collected from noon local standard time weather readings. Although the FWI was originally developed for forest fire danger estimation in Canada (Van Wagner 1974), several authors have extended its use to Europe and shown that high values of the FWI are linked to high levels of forest fire risk (Camia *et al.* 1999, Viegas *et al.* 2000).

First described in 1974 (Rouse *et al.* 1974), the NDVI can be extracted from satellite sensor data using a combination of visible and near-infrared light reflected by vegetation. NDVI can thus be derived from images acquired by the National Oceanic and Atmospheric Administration Advanced Very High Resolution Radiometer (NOAA-AVHRR). Several authors related low values of NDVI to high levels of fire risk (Lopez *et al.* 1991, Illera *et al.* 1996, Aguado *et al.* 2002, Maselli *et al.* 2003).

The indices, the FWI and NDVI, are computed daily over Europe during the fire season (May to October) as part of the European Forest Fire Information System (EFFIS; San-Miguel-Ayanz *et al.* 2002). However, a comparison of the ability of the two indices to forecast fire risk has not yet been performed, probably because the different data sources and methodologies involved in the computation of the indices make them not immediately comparable.

There are several approaches for comparing the performance of statistical indices. Some approaches are based on a graphical comparison of the statistical distribution of the indices. They highlight graphically statistical differences of the distributions. Indices having nearly equal distribution of the values would be considered the same. Additionally, indices can be compared using mathematical measures of difference. Some of these are the Mahalanobis distance, the Jeffrey–Matusita and the Kappa statistic. They have been used extensively in remote sensing image classification. Alternatively, the performance index and the performance ratio index (Mandallaz and Ye 1997) compare the performance of an index against pure chance, and are therefore best suited for the comparison of statistical distributions of fire ignitions over large areas. Unlike the use of graphical analysis, these indices permit a quantitative evaluation that is independent of the index of risk and allows an immediate comparison of results.

The aim of this work was to compare the performance of the FWI and the NOAA-AVHRR-derived NDVI in forest fire risk assessment. The two specific objectives were:

- to perform a qualitative comparison of the FWI and the NDVI using a frequency distribution analysis over a 10-year period, and
- to carry out a quantitative comparison of the indices using the performance index and the performance ratio index proposed by Mandallaz and Ye (1990).

2. Data description and preprocessing

Two main data sources were used in this study for the computation of the FWI and the NDVI fire risk levels. NDVI values were computed from satellite imagery data acquired by the NOAA-AVHRR sensor, while FWI data were computed from meteorological observations acquired by a grid of meteorological stations spread throughout Europe.

A time series of NOAA-AVHRR NDVI and FWI daily data from 1989 to 1999 for the whole of Spain was considered for analysis. The time series covered the period from 1 May to 31 October for each year. This period, characterized by small precipitation amounts, corresponds to the fire campaign period in the Mediterranean countries (European Commission 2003*a*) and is the one with the highest number of fires in Spain (figure 1).

Atmospheric correction and radiometric calibration using post-flight coefficients were applied to the raw NOAA-AVHRR optical bands as described in Tanre *et al.* (1990) to obtain reflectance values from which the NDVI was computed. Data from 1994 were discarded because of consistent errors in the NDVI images. To overcome the low positional accuracy of the AVHRR images provided by the satellite orbital parameters, the spatial resolution of the NDVI images was resampled to 4.4 km^2 by averaging all the land and cloud-free pixels contained in the corresponding 4×4 pixel window from the original 1.1 km^2 spatial resolution images. Subsequently, a 10-day Maximum Value Temporal Filtering (MVTF) image

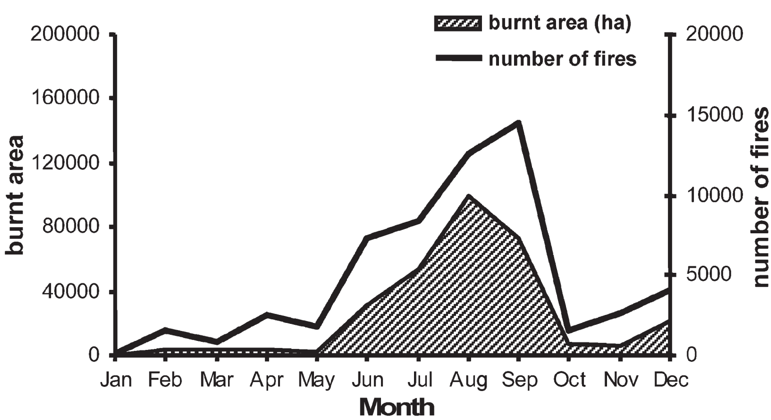


Figure 1. Distribution of number of fires and area burnt by month in 2001 for Germany, Spain, France, Italy and Portugal (Source: DG-AGRI, European Commission 2003).

(Arce and McLoughlin 1987) was obtained for each day of the study period adopting a moving temporal window of 10 days. Each MVTF retained the highest NDVI value of each pixel in the scene during a 10-day period, considering the current day and the previous 9 days. The MVTF procedure is a standard procedure to reduce image noise caused by clouds, aerosols and water vapour.

The available meteorological database covers homogeneous and continuous data throughout Europe. It consists of daily meteorological measures recorded at 1200 h from about 360 ground weather stations throughout Europe. The measures have been spatially interpolated over 1389 square grid cells of 50 km^2. Hence, a daily FWI image was available for all the fire campaign period during the study period.

Information on land cover in the study area was derived from the Coordination of Information on the Environment (CORINE) Land Cover database (European Commission 1993). The CORINE Land Cover database divided the European territory into 44 different classes grouped in three levels of detail. A mask of vegetation was derived retaining only pixels corresponding to forests and semi-natural areas and resampling them to 4.4 km^2 spatial resolution. Table 1 presents these CORINE classes.

Fire event information was extracted from the European Forest Fire Information System (EFFIS), which contains information on single fire events collected in the framework of European Regulation EC 2152/2003 concerning monitoring of forests and environment interactions in the European Community (European Commission 2003*b*). These data include information on the location of the fire, ignition time (year, month and day) and information about the burnt area at an administrative commune level. The definition of administrative commune level adopted was the one defined by Geographic Information System of the European Commission (GISCO) (Eurostat 2004). A subset of this database for the period from 1989 to 1999 was considered (figure 2). Only fires larger than 50 hectares were retained for this analysis because these are responsible for most of the forest fire damage in the Mediterranean region (European Commission 2004).

3. Methods

The methodology used in this study consisted of four major steps: (1) subdivision of the study area into two strata to minimize the variance of the NDVI and FWI values

Table 1. European CORINE Land Cover database classes considered for the vegetation mask.

Level 1	Level 2	Level 3
2. Agricultural areas	2.4 Heterogeneous agricultural areas	2.4.3 Land principally occupied by agriculture, with significant areas of natural vegetation
		2.4.4 Agro-forestry areas
3. Forest and semi-natural areas	3.1 Forests	3.1.1 Broad-leaved forest
		3.1.2 Coniferous forest
		3.1.3 Mixed forest
	3.2 Shrub and/or herbaceous vegetation association	3.2.1 Natural grassland
		3.2.2 Moors and heathland
		3.2.3 Sclerophyllous vegetation
		3.2.4 Transitional woodland shrub
	3.3 Open spaces with little or no vegetation	3.3.3 Sparsely vegetated areas

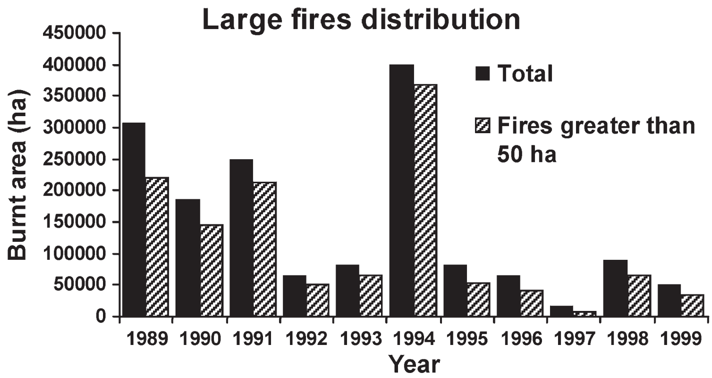


Figure 2. Area burned by fires larger than 50 ha compared to the total burnt area in Spain.

within each stratum, (2) extraction of NDVI and FWI values for each individual commune, as fire events are recorded at the commune level, (3) plotting of the NDVI and FWI distributions next to the fire event distributions, and (4) statistical analysis of the efficiency of the NDVI and FWI in identifying fire risk scenarios using the performance index and the performance ratio index.

To reduce the large variability of the NDVI values over the whole of Spain, the territory was divided according to the range of variation of the NDVI values. Of the several statistical methods for the classification or ranging of interval/ratio data, one of the most common in cartography is the natural breaks method based on a subjective recognition of gaps in the distribution. This method, developed by Jenks and Caspall (1971), minimizes variation within classes and maximizes variation between classes. It involves plotting a histogram of the data to highlight gaps. The histogram of the average NDVI values during the considered time series was plotted, and a gap in the distribution was detected at an NDVI average value equal to 0.55 (figure 3). As a result, the territory was divided into two zones (figure 4). Zone 1 was characterized by pixels having an average value >0.55 and zone 2 was characterized by pixels having an average value <0.55.

It was observed that the typical Atlantic zone with a slight water deficit during the summer was characterized by higher average values of NDVI whereas the typical

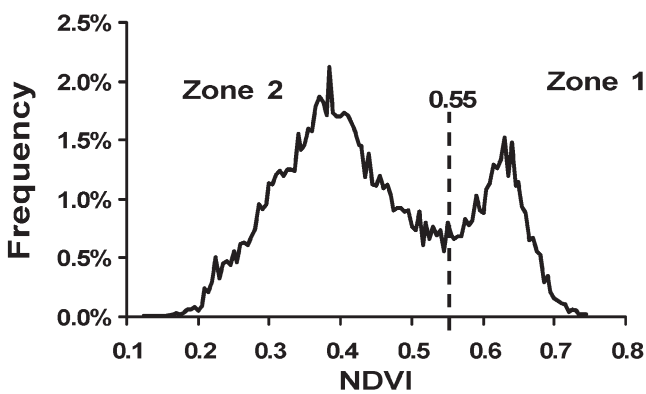


Figure 3. Histogram of the average NDVI values observed in the study period. 0.55 represents the NDVI value considered as threshold between zones 1 and 2.

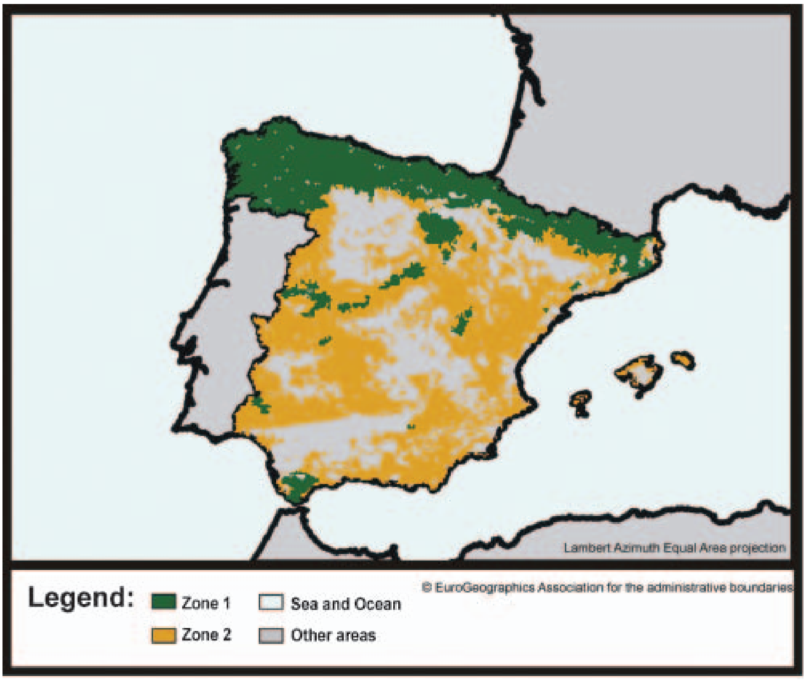


Figure 4. Territory division by considering the average values of the NDVI for the study period.

Mediterranean zone with a much lower precipitation during the summer was characterized by lower average values of NDVI. To obtain a reliable comparison of the results, the same territory division was also applied to the FWI data.

The minimum daily NDVI-MVTF value and the maximum FWI at the administrative commune level (Eurostat 2004) were selected as the representative daily values for the commune, as they represented the highest fire risk condition within that administrative boundary.

The relative frequency distribution of NDVI and FWI values was extracted for the entire time series of data. This was compared to the distribution of fire occurrence grouped by NDVI and FWI values. The plot of both distributions should be different if they are statistically different. The difference between both distributions is a prerequisite for the use of the index for discriminating different levels of fire risk. Only then is it possible to determine the connection between NDVI or FWI values and the level of forest fire risk.

As the plotting of the relative frequency distribution only permits a qualitative evaluation of the results, an analysis based on the performance index and the performance ratio index was also performed. These indices permitted a quantitative evaluation that was independent of the index and that allowed an immediate comparison of results obtained using different indices. They compared the performance of a considered index of risk with the performance obtained using a random value instead. Thus, they evaluated the value added of using the level of risk provided by the index. As suggested by Mandallaz and Ye (1997), the use of randomness is the only method that can be fitted to every data set and that allows historical comparisons.

For each day, the index values of the communes with fires were extracted and compared with the index values of the communes that did not suffer fires. The indices computed for each day were:

$$I_{\mathrm{p}} = \sum_{i=1}^{N} \mathrm{rank}*(zi)Ii \qquad [1]$$

$$I_{\mathrm{random}} = \frac{d(N+1)}{2} \qquad [2]$$

$$I_{\max} = \frac{d(2N+1-d)}{2} \qquad [3]$$

$$I_{\mathrm{ratio}} = \frac{I - I_{\mathrm{random}}}{I_{\max} - I_{\mathrm{random}}} \in (0,\ 1) \qquad [4]$$

where zi is the NDVI, or FWI, value of the commune i; rank*(zi) $\in \{1, 2, \ldots, N\} = N - \mathrm{rank}(zi) + 1$ for NDVI or $= \mathrm{rank}(zi)$ for FWI; rank(zi)=rank of zi; Ii=random indicator variable on commune i (0 if there were no fires, 1 otherwise); d=number of fires; and N=number of communes.

I_{p} [1] represents the computed value of the performance index for each day and I_{random} [2] the corresponding value of the performance random index. The comparison between I_{p} and I_{random} evaluates the added value by using the index values instead of random values, and therefore I_{p} should be greater than I_{random}.

The values of risk computed for each commune were collected every day and inserted in a list arranged in ascending numerical order. The position of the values of risk assumed by each burnt commune in the considered day in the ordered list, referred to as the ranking value, were retained and summed in order to compute the performance index, I_{p}. The ideal condition obtainable is to have the values of the index of risk of all the burnt communes assuming the highest ranking possible value because, in principle, a high level of risk is represented by a high value of the index. For each month, the number of days with fires in which I_{p} assumed a value greater than I_{random} was reported. This helped in evaluating the number of days in which the use of the considered index of risk gave an added value in comparison to the use of pure chance.

The $I_{\max}$ [3] represents the largest possible value of the performance index for the considered day and corresponds to the ideal condition. The I_{ratio} [4] represents the performance ratio. In the case the index performed better than using random values of risk, it evaluates how much better it performed and how far away it was from choosing the values randomly. Moreover, it permits a direct comparison of the performances of different indices. In the process of computation of I_{ratio}, all the negative values of the index I_{p} lower than I_{random} were rounded to zero. The monthly value of I_{ratio} was obtained by averaging all the daily I_{ratio} values observed in the month considered.

4. Results and discussion

Figure 5 shows the relative frequency distribution of NDVI values computed, together with the number of fire events that occurred assuming different values of NDVI. The corresponding distributions for the FWI are shown in figure 6. A prerequisite for the indices to discriminate the level of risk was that their frequency distributions were different from the distributions of forest fire events in the study period. The expected result was a distribution in number of fires shifted towards lower values of risk, low values for NDVI and high values for FWI, as compared to

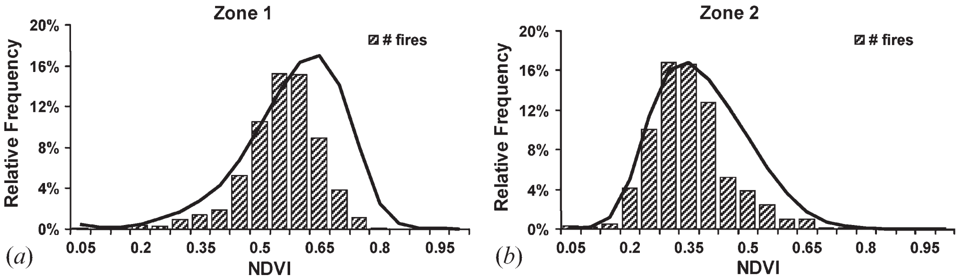


Figure 5. Relative frequency distributions of the NDVI values and number of fires by NDVI values for (*a*) zone 1 and (*b*) zone 2.

the general distribution of frequencies of the indices. Although the results were only qualitative, the difference between NDVI and FWI was immediately apparent. A clear displacement was found between the distribution of the FWI values and the distribution of forest fire events. This implies that there are underlying statistical differences between the distributions.

In the case of the NVDI, the relative frequency distribution of values and the distribution of fire events showed a similar behaviour. This was particularly notable for the maximum values, which were the most frequent values in both distributions. Thus, it was observed that most fires occurred in areas that presented NDVI values close to the most frequent values in the NDVI distribution (figure 5). Thus, an index value could be observed only because it was the most probable during a particular day and not because it was strictly related to a situation of high risk.

The performance index I_p was introduced to evaluate quantitatively the performance of an index of risk in a daily context.

The results obtained for the analysis of the performance index are shown in figure 7. For both zones, the number of days in which the index of risk presented better results than the use of a random value was reported on a monthly base. The global results (Year), collecting all the months, highlighted the better performance of the FWI compared with the NDVI. The best performance was obtained by the FWI in zone 2, especially in May and June (figure 7(*b*)). The worst performances were obtained by the NDVI during August and September in zone 2, where the NDVI assumed a result lower than the 50% represented by the horizontal line in the figure, which means that for half of the observed days the NDVI did not provide added information compared to the use of randomness.

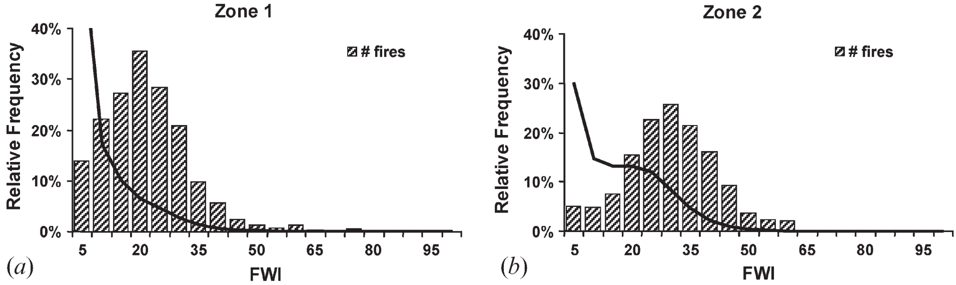
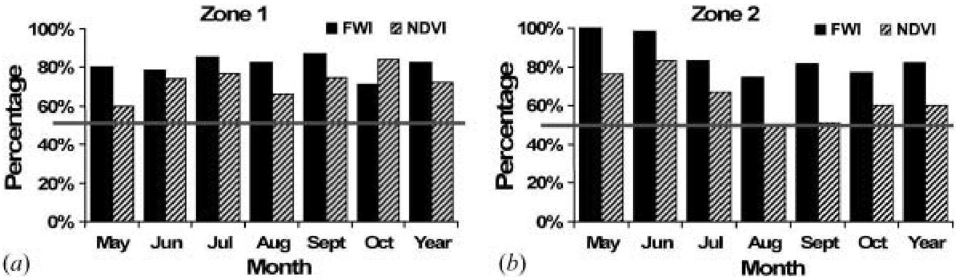


Figure 6. Relative frequency distributions of the FWI values and number of fires by FWI values for (*a*) zone 1 and (*b*) zone 2.



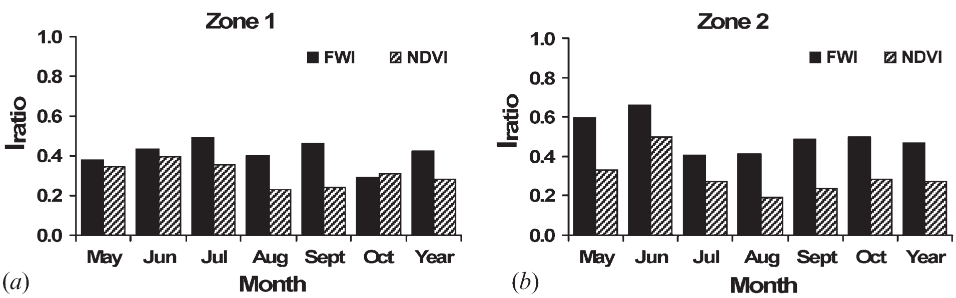
(*a*) (*b*)

Figure 7. Number of days the value of the performance index computed for the NDVI and FWI was larger than its relative random value. Results are for the analysis by month and the analysis for the entire time series (Year). The horizontal line represents 50%.

To compare the performances of the two indices of risk, the ratio performance index I_{ratio} was computed and the results are presented in figure 8. The maxima value (i.e. one) refers to the best observable case in which all the fire events occurred assuming the highest level of risk for the adopted index. Even if the general performances dropped for both indices during the summer, the FWI presented better global and monthly results in comparison to those obtained with the NDVI.

The study of the distribution of NDVI values in communes having fires highlighted the tendency for a fire to occur assuming a value close to or equal to the most probable in most of the observed events (figure 5). This tendency was further analysed by the use of the performance indices. These results highlight how the NDVI values in areas subjected to fires are not significantly different from those in the areas without fires, especially during the summer. This is probably because vegetation water stress is almost the same over nearly the whole of the Mediterranean region of Spain during the same period; consequently, areas subject to fire and surrounding areas present similar characteristics in relation to susceptibility to fire ignition and spread. For instance, figure 7(*b*) shows how the NDVI performed better than the use of random values on half of the observed days. The NDVI used in this study was computed on a 4 km × 4 km window, which is a higher resolution than that of the forest fire event data (commune level). Therefore, the resolution of the satellite imagery did not affect the overall performance of the NDVI.

In the case of the FWI, a statistical difference between the distribution of values observed in the burnt area and the general distribution of values all over the



(*a*) (*b*)

Figure 8. Comparison of the average of the ratio of performance index computed for the NDVI and the FWI. Results are for the analysis by month and the analysis for the entire time series (Year).

territory was observed. In particular, fire events tend to occur assuming a distribution of values centred on a higher value of the FWI (figure 6). This was interpreted as the tendency for a fire to occur assuming higher values of the FWI, which was related to a high level of risk. The performance index highlighted the ability of the FWI to produce added information, better than randomness, in most of the observed days. In particular, the year analysis of the FWI demonstrated that it produced better results than using a random value in 83% of the considered days in zone 1 (figure 7(*a*)) and in 82% of the considered days in zone 2 (figure 7(*b*)).

5. Conclusions

The ratio performance index demonstrated the greater potential of the FWI to assess fire risk as compared to the NDVI. The FWI presented results better than the NDVI in all cases (figures 8(*a*) and 8(*b*)), with the exception of October in zone 1. Nevertheless, the results in this latter case were comparable to those obtained with the NDVI.

It is therefore possible to conclude that the FWI produced better results than the NDVI. Additionally, the results of this study indicate that the NDVI is not able to discriminate levels of fire risks. This negative behaviour of the NDVI as a fire risk index is further aggravated during the summer season in the Mediterranean region, the period in which the NDVI produced the worst performance.

The present study also demonstrates, by analysing the behaviour of different indices in a large territory and in an extended time period, that the estimation of vegetation condition does not provide information that would permit significant discrimination within a region of different levels of fire risk. The better performance obtained by the FWI, which is based on meteorological information, is probably linked to the strong influence of the weather conditions in the distribution of forest fires. Although the study was not performed for the whole of the Mediterranean basin, it is likely that the results and conclusions can be extrapolated to the total area.

References

Aguado, I., Chuvieco, E., Martin, P. and Salas, J., 2002, Assessment of forest fire danger conditions in southern Spain from NOAA images and meteorological indices. *International Journal of Remote Sensing*, **24**, pp. 1653–1668.

Arce, G.R. and McLoughlin, M.P., 1987, Theoretical analysis of the max/median filter. *IEEE Transactions on Acoustics, Speech and Signal Processing*, **35**, pp. 60–69.

Camia, A., Bovio, G., Aguado, A. and Stach, N., 1999, Meteorological fire danger indices and remote sensing. In *Remote Sensing of Large Wildfires in the European Mediterranean Basin*, E. Chuvieco, (Ed), pp. 39–59, (Berlin: Springer).

Canadian Forestry Service, 1970, *Canadian Forest Fire Weather Index* (Ottawa: Canadian Forestry Service, Department of Fisheries and Forestry).

European Commission, 1993, *CORINE Land Cover: Technical Guide*, EUR12585 (Luxembourg: Office for Official Publication of the European Communities).

European Commission, 2003a, *Community Forest Fire Information System: 2003 Report Data for 1985–2001* (European Commission Directorate-General for Agriculture, DG AGRI-FI).

European Commission, 2003b, Regulation (EC) No. 2152/2003 of the European Parliament and of the Council of 17 November 2003 concerning Monitoring of Forests and Environmental Interactions in the Community (Forest Focus). *Official Journal of the European Union* L 324/1.

European Commission, 2004, *Forest Fire in Europe – 2003 Fire Campaign* Official Publication of the European Communities.

EUROSTAT, 2004, *The GISCO Database Manual* (Luxembourg: Eurostat).

ILLERA, P., FERNANDEZ, A. and DELGRADO, J.A., 1996, Temporal evolution of the NDVI as an indicator of forest fire danger. *International Journal of Remote Sensing*, **17**, pp. 1093–1105.

JENKS, G.F. and CASPALL, F.C., 1971, Error in choroplethic maps: definition, measurement, reduction. *Annals of the Association of American Geographers*, **91**, pp. 217–244.

LOPEZ, S., GONZALEZ-ALONSO, F. and LLOP, R., 1991, An evaluation of the utility of NOAA AVHRR images for monitoring forest fire risk in Spain. *International Journal of Remote Sensing*, **12**, pp. 1841–1851.

MANDALLAZ, D. and YE, R., 1997, Prediction of forest fires with Poisson models. *Canadian Journal of Forest Research*, **27**, pp. 1685–1694.

MASELLI, F., ROMANELLI, S., BOTTAI, L. and ZIPOLI, G., 2003, Use of NOAA-AVHRR NDVI images for the estimation of dynamic fire risk in Mediterranean areas. *Remote Sensing of Environment*, **86**, pp. 187–197.

MINISTERIO DE MEDIO AMBIENTE, 2004, www.mma.es/portal/secciones/biodiveridad/defensa_incendios/estatisticas_incendios.

PYNE, S.J., ANDREWS, P.L. and LAVEN, R.D., 1996, Wildland fire fundamentals. In *Introduction to Wildland Fire*, pp. 3–45 (New York: Wiley).

ROUSE, J.W., HAAS, R.H., SCHELL, J.A. and DEERING, D.W., 1974, Monitoring vegetation systems in the great plains with ERTS. In *Proceedings of the Third ERTS Symposium*, (Maryland: NASA), pp. 309–317.

SAN-MIGUEL-AYANZ, J., 2002, Methodologies for the evaluation of forest fire risk: from long-term (static) to dynamic indices. In *Forest Fires: Ecology and Control*, A.T. Carraro and V. Carraro (Eds), pp. 117–132 Italy: University degli Studi di Padova).

SAN-MIGUEL-AYANZ, J., BARBOSA, P., SCHMUCK, G. and LIBERTA, G., 2002, Towards a coherent forest fire information system in Europe: the European Forest Fire Information System (EFFIS). In *Forest Fire Research and Wildland Fire Safety*, D.X.E. Viegas, (Ed) (Rotterdam: Millpress).

TANRE, D., DEROO, C., DUHAUT, P., HERMAN, M., MORCRETTE, J.J., PERBOS, J. and DESCHAMPS, P.Y., 1990, Description of a computer code to simulate the satellite signal in the solar spectrum: the 5S code. *International Journal of Remote Sensing*, **11**, pp. 659–668.

VAN WAGNER, C.E., 1974, *Structure of the Canadian Forest Fire Weather Index* (Ottawa: Environment Canada Forestry Service).

VELEZ, R. and MERIDA, J.C., 2002, Forest fire management in Spain: some examples of systematic analysis of a comprehensive database to improve effectiveness and efficiency. In *Forest Fire Research and Wildland Fire Safety*, D.X. Viegas, (Ed) (Rotterdam: Millpress).

VIEGAS, D.X., BOVIO, G., FERREIRA, A., NOSENZO, A. and SOL, B., 2000, Comparative study of various methods of fire danger evaluation in Southern Europe. *International Journal of Wildland Fire*, **9**, pp. 235–246.