MONITORING FOREST REGROWTH RATES AFTER FIRES WITH MULTITEMPORAL LANDSAT TM IMAGERY

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ABSTRACT

The aim of this work is to monitor the recovery process after fire by means of satellite imagery. The objective is to assess the ability of different species populations to regain initial NDVI values when they are subject to disturbance, to analyze the speed of recovery in the following years after fire, and finally, to estimate rates of regrowth. The test area is located in the north of the province of Alicante, in the Mediterranean coast of Spain. This area is especially prone to forest fires, showing a remarkable land use history and human pressure. The test areas belong to different microclimatic zones and show diverse vegetation communities, so we attempt to discover different behaviours according to biogeographical conditions. To accomplish these objectives, we obtained nine Landsat 5 TM images from 1984 to 1994 on which geometric and radiometric corrections were carried out. When the comparison between images was possible, we generated the NDVI for each date. The NDVI and the differences between images were the most suitable parameters to map the burnt areas. In addition, to assess the recovery processes a non-linear regression analysis between multitemporal NDVI values and the time elapsed from the fire was used. The mathematical adjustment between NDVI and TIME showed an asymptotic behaviour when the recovery process was complete. In addition, this adjustment provided parameters with an interesting ecological interpretation more related to the regeneration process after fires.

1. INTRODUCTION

Postfire studies have been carried out by several authors with diverse objectives (recovery processes, mapping damage intensities or burned lands), being the use of vegetation indices (VIs) the common factor in their methodologies (Jakubauskas *et al.*, 1990; Navarro, 1991; Viedma and Chuvieco, 1993). A close relationship has been demonstrated between VIs and the physiologic parameters of vegetation (LAI, biomass, photosynthetic activity, productivity, etc..) (Huete, 1987, Sellers, 1987; Asrar, 1992; Baret and Guyot, 1991). Although LAI is the principal morphological parameter of the vegetation canopy linking to satellite-derived vegetation indices (Tucker and Sellers, 1986; Baret *et al.*, 1989), its estimation and measurement is very difficult. For that reason the VIs have become a valuable tool to monitor and assess vegetation status.

The spectral behaviour of vegetation in the visible and near infrared region in contrast to soils justifies the use of NDVI in vegetation cover discrimination. In addition, NDVI partly normalizes the influence of external factors in the canopy reflectance, i.e. the errors associated with illumination fluctuations or atmospheric scattering (Holben *et al,* 1986).

On the other hand, in several regeneration studies regression and correlation analyses have been used to describe the relationship between TM band values and age of regenerated stands (Fiorella and Ripple, 1993). Other authors have studied the regeneration process creating transition matrix between the prefire image classification and the postfire one (Gregory *et al.*, 1981; Kachi *et al.*, 1986; Hall *et al.*, 1987). These comparisons have been widely used although the results had problems due to the effect of classification errors on transition rate estimates. However, from transition matrices it is possible to estimate the recurrence time (the average number of years for a landscape element to return to a given state once it has left the state) (Hall *et al.*, 1991).

In this paper, we used the Normalized Difference Vegetation Index (NDVI) in reflectance values:

$$NDVI = \frac{TM4 - TM3}{TM4 + TM3}$$

to analyze the regeneration process by an adaptation of a reflectance model (Baret, 1988) that allows an empirical relationship to be established between canopy reflectance (measured as NDVI) and LAI values. This model describes the growing process of canopies without any disturbance phenomena, being the NDVI values defined as a function of LAI and showing a direct relation between LAI and time. According to the relationships between canopy reflectance, biological parameters (LAI-ground cover) and time, we adapted the original model to describe the regenerative processes after fires in a forested area of the Mediterranean coast of Spain, historically disturbed by fire.

2. METHODOLOGY

2.1. The Study Area

The study area is located in the north of the province of Alicante, on the Mediterranean coast of Spain. The area is bounded by the UTM coordinates X 730400-760400, Y 4274000-4304000 with a surface of 900 Km^2. This area is especially prone to forest fires, showing a remarkable land use history and human pressure. Geomorphologically this zone presents alternate mountains and valleys with NE-SW direction whose lithology are limestones, marls and sandstone from the Mesozoic Era and constitutes the most eastern part of the "Beticas" chain. The elevation ranges between sea level and 1530 meters. The major parts of the forested areas are located between 400-900m, while the agricultural zones are distributed between 0-300m covering the areas with the best topographic conditions (Figure 1).

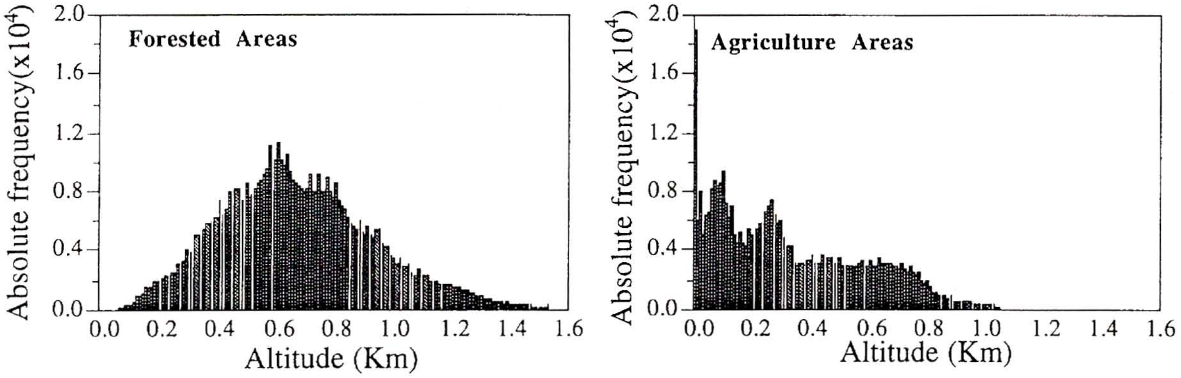


Figure 1 - Altitudinal distribution of the forested and agricultural zones in the study area

The natural vegetation of this area is the typical Mediterranean forest growing in a limestone substratum. This forest is a heterogeneous formation composed mainly of holm-oaks (*Quercus rotundifolia*) considered to be the "climax vegetation", which has given way at present to coniferous species (*Pinus halepensis*, *Pinus pinaster*) and to secondary formations of shrublands, originated from the degradation of the climax vegetation (*Quercus coccifera*, *Ulex parviflorus*, *Rosmarinus officinalis*, *Thymus vulgaris*, *Stipa tenacissima*,). In this study we have differentiated three types of vegetation communities as identifiable categories in the digital classification of the images. Their physiognomy and species composition are described below:

i) Sparse Shrubs: They form open communities with a low density and high surface of bare soil. The thymes and rock roses are the more common species. They are located on the steeper slopes where erosion processes are more accentuated, but it is also usual to find them in topographically and edaphically favourable areas due to human pressure and to the great recurrence of fires. So, physiography is not the only determinant factor in their location.

(ii) Dense Shrubs: They are dense and close communities with a medium-high height (0.5-1m). The species composition is similar to the sparse shrubs although the level of closure is greater. thymes, rosemaries, moors and furzes are the commonest species.

(iii) Forested Shrubs: These are dense shrub communities with a sparse tree canopy. These trees respond to reforestation practices and natural regeneration from fires. The commonest species is *Pinus halepensis*.

In general, the spatial distribution of the natural vegetation cover is very fragmented and the distribution of forest areas and their density levels respond more to human activities than the natural physiography and topographic conditions.

Climatologically, the topographic complexity of this area leads to diverse microclimatic conditions that produce different environmental states. The average annual precipitation varies from 350 mm in the South to 900 mm in the North. This steep rainfall gradient allows a classification into three microclimatic areas: less than 450 mm, between 600-700 mm and more than 800 mm. According to this classification, we have differentiated three regions denoted by the following abbreviations, and later we will use them to describe the training areas:

VG ("Vall de La Gallinera"): it is the wettest area (more than 800 mm). Located at the North of the study area.
VE ("Vall de Ebo"): follows the previous area to the South direction. It is very wet too (between 600-700 mm.).
EG ("Embalse de Guadalest"): it is the driest area (less than 450 mm). It is situated in the south-east zone of the study region.

2.2. Imagery Acquisition

In order to perform this multitemporal study, several Landsat TM images from 1984 to 1994 have been used. The date selection was performed taking into account the statistical information available (forest fire data base), the seasonal incidence of fire (summer) and the absence of clouds. The images were the following:

April 7th 1984
April 9th 1986
June 3rd 1987
May 7th 1989
June 7th 1990
June 14th 1991
March 28th 1992
June 19th 1993
May 21st 1994

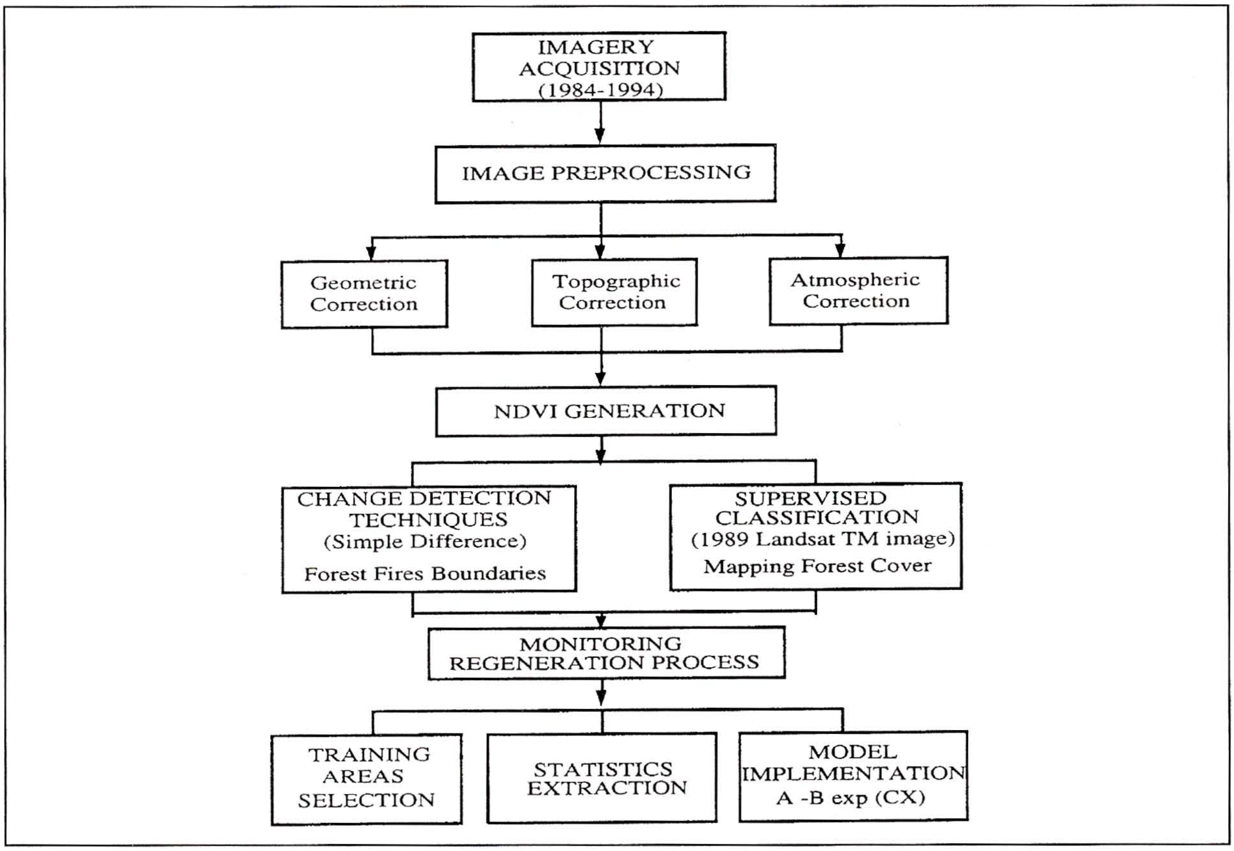


Figure 2 - Flow diagram of the methodology followed in this study.

2.3. Images Preprocessing

The image preprocessing consisted of geometric and radiometric (topographic and atmospheric) corrections (Figure 2). These treatments made possible the comparisons between images. In the first place, all scenes were converted to apparent reflectances using sensor calibration coefficients.

Later, an empirical atmospheric normalization of the multi-annual images was employed to avoid the effects of the different atmospheric conditions of the images and problems related to the absolute calibration of the sensors due to the degradation process. As we did not know the atmospheric conditions during image acquisition, the satellite reflectances from invariant ground targets (which are assumed not to change in time) were used to normalize multitemporal datasets with respect to one reference image, preferably that one with the lowest contribution of atmospheric reflectance (Lopez and Caselles, 1987; Hill and Sturm, 1991). The reference image was May 7th 1989 and a selection of stable radiometric areas (sand and water) were chosen from the TM scenes (Figure 3b). These invariant picture elements were compared to those from the reference image by computing the respective linear band-to-band regression (Figure 3a). In this way, any differences in the apparent reflectances of such target surfaces was assumed to be due to differences in path radiance, atmospheric attenuation and sensor degradation.

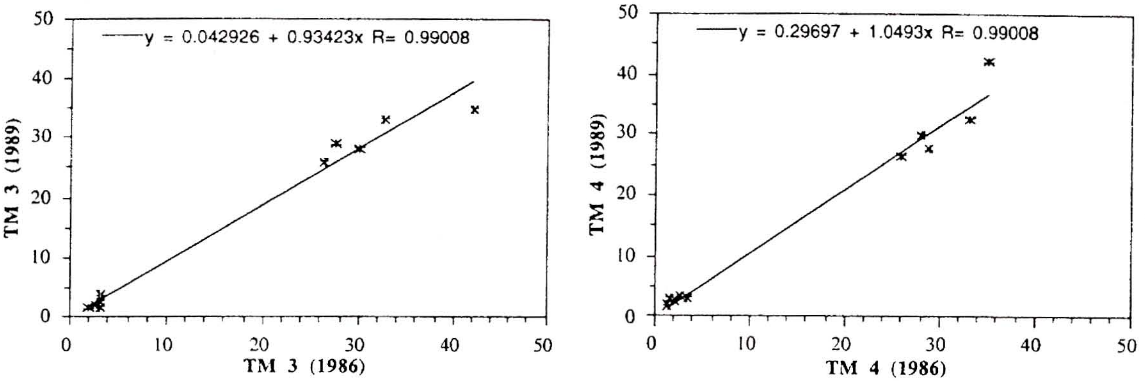


Figure 3a - Linear band-to-band regression between reference image (1989) and another TM scene to accomplish an empirical atmospheric normalization of the multiannual images used.

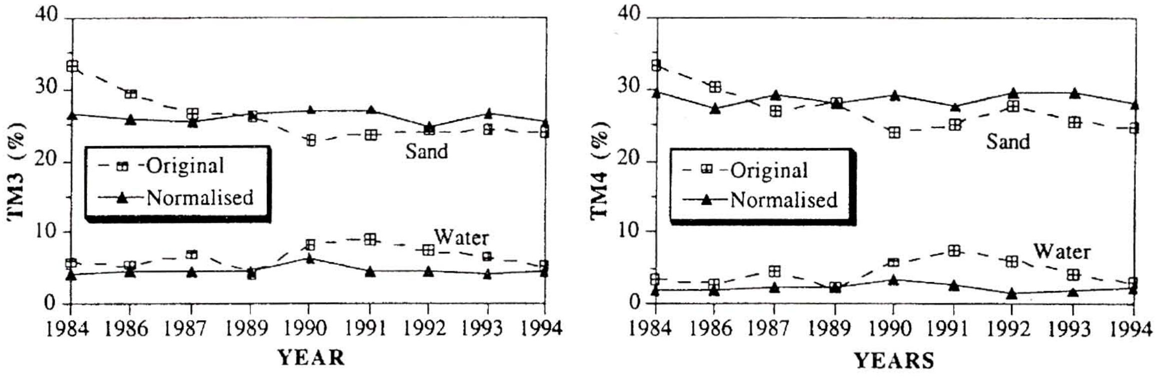


Figure 3b - Reflectance values of stable radiometric areas (sand and water) before and after the multiannual atmospheric normalization.

The radiometric correction of topogOraphically induced effects on scene radiance was carried out by means the Minnaert method (Minnaert, 1941). This is a modified slope-aspect semi-empirical method based on the common cosine correction. According to this method the amount of the radiance in each point (LH) is proportional to the cosine of the incidence angle *i*, where *i* is defined as the sun's incidence angle in relation to the normal on a pixel, the sun's zenith angle *sz*, the radiance observed over sloped terrain (L_T) and the Minnaert constant *k*. The parameter *k* is considered to be a measure of the extent to which a surface is Lambertian and can be calculated empirically by linearizing the equation 1 logarithmically and estimating the slope of a linear regression (Teillet *et al.*, 1982; Meyer *et al.*, 1993).

$$L_H = L_T\left[\frac{\cos(sz)}{\cos(i)}\right]^k \tag{1}$$

When the images were radiometrically comparable, a multitemporal classification was carried out. After removing crops and other land uses (urban areas, water bodies, etc.) using a mask, the natural vegetation was classified into sparse, dense and forested shrubs, coniferous forests and bare soils. With this mask, the forest fires were drawn by means differences among prefire and postfire NDVI images. Later, we extracted the NDVI multitemporal values for the areas burned in 1984-5 and not burned later during the time analyzed because these zones showed the longest postfire-time. And finally, these wildfires were classified to observe if there were some variations in the recovery process for different vegetation communities.

2.4. Monitoring Recovery Processes

As is known, LAI is a basic morphological parameter of vegetation canopy linked to satellite-derived vegetation indices (Tucker and Sellers, 1986). This relationship between NDVI and LAI has been widely studied (Price, 1992; Bouman, 1992; Asrar *et al*; 1992; Peterson *et al.*, 1987).

Experimental results have confirmed that NDVI increases exponentially with LAI and it seems to reach a plateau at high LAI levels when the vegetation cover is maximum (Nemani *et al.*, 1993; Bausch, 1993; Garcia-Haro *et al.*, 1995). In addition, for low vegetation levels, NDVI variations are linearly dependent on LAI values. Otherwise, at intermediate canopies, NDVI presents soil-colour induced variations, due to the scattering and transmission of NIR flux through the canopy (Huete *et al.* 1985). The asymptotic value of NDVI is reached at certain LAI values, depending on the optical and architectural characteristics of the canopy stand (Peterson *et al.*, 1987). This saturating value is independent of soil optical properties, because it occurs when soil is completely hidden by leaves.

We applied the following empirical expression to model the exponential relationship observed between NDVI and LAI, which has been reported by several authors (Baret *et al.*, 1989; Wiegand *et al.*, 1992).

$$NDVI = A - B * \exp(-C*LAI) \qquad (2)$$

In that expression, A is the $NDVI\infty$, i.e., the limiting value of the NDVI at large LAI values. (A-B) is the intercept of the curve with the NDVI axis, i.e., the $NDVI_0$ for the soil background; B is, therefore, well related with the soil optical properties. A and B should be expressed in units of NDVI. Finally, C is a coefficient related to the extinction of solar radiation through the canopy and should be expressed in units of $(LAI)^{-1}$.

In this work we aimed to quantitatively analyze the variations of vegetation during the years following the fire, in order to address the factors affecting regenerative processes. In this way, we can assume a direct relationship between the time elapsed from a forest fire and LAI (consequence of vegetation growth in the burned areas). The equation (2) was now applied replacing vegetation contribution expressed by the LAI values for time lapsed since the fire occurred:

$$NDVI = A - B * \exp(-D*TIME) \qquad (3)$$

where the parameters A and B have a similar meaning as in equation 2 and the parameter D is expressed in units of $(time)^{-1}$. This representation allows us to determine the evolution of the NDVI through some variables (such as A, B, D and some others derived from these), which provide an ecological interpretation well related to the regeneration process after fires.

In this sense, A (with NDVI values) represents the "**Potential Vegetation**" that the forest areas can reach if there is not any biophysical constraint or disturbance. This constant can establish differences between areas and communities due to the diverse regenerative capabilities offered in the long run. Hence, the constant A lets us define the "**potential recovery capability**" of the communities. If this magnitude shows high values, it represents a great recovery ability. However, if this one shows low values, the recovery capability will be low. This constant depends on the degree of degradation of the prefire vegetation community.

B (with NDVI values) is the variation of the NDVI values from the fire (A-B) until a great lapse of time (A) enough to reach a complete recovery. Hence, this constant is in direct relation with the constant A, and describes the "**magnitude of change**" produced by the fire over the potential vegetation community. By comparing NDVI values before and immediately after the fire, we could assess the magnitude of the change on the real state of vegetation and the ability of the ecosystem to reach similar values as before the fire.

D (with T^{-1} dimension) is the constant that indicates the speed at which the vegetation communities reach stability. Hence, the constant D represents the "**stability speed**". This parameter indicates the temporal scale of the regeneration process. In this sense, if the D value is high the areas can reach the "stability state" in a short time period, but if value is low, the areas remain in a continuous "growth process" due to the physiologic conditions of the communities (species populations of short life cycle).

With the slopes of the curves, we tried to express the **"speed of recovery"** of the burned communities. However, this information only makes sense if it is analysed simultaneously with the other constants. Hence, high slopes will mean a great recovery speed if accompanied by high A values, but it only can express the magnitude of the change if is accompanied by high B values and low A values. On the other hand, when the slopes and A are low the recovery speed is slow and represents the low magnitude of change caused by the fire. Later, you can see that the slope was studied during the first four years after fire because the major changes happen during that period.

3. RESULTS

In the vegetation communities analyzed, we observed two well differentiated recovery pathways. On the one hand, the recovery behaviour is near linear (Figures 4 and 5), showing low D values and high A values. In this situation, the saturation level of the NDVI (A constant) during the time series analysed was not reached. And hence, the D constant (that is in direct relation with A) shows an overestimated low value. In this sense, we agree with the results of Wiegand *et al* (1992) that the iterative procedure either fails to converge on values of A and D or arrives at large values of A that are offset by unrealistic small values of D, both of which are uncertain. The ecological interpretation of this near-linear recovery behaviour can be given by the physiologic characteristics of the vegetation communities (species populations having a short life cycle), which are kept in a "continuous growth process" for a long time without reaching stability in their recovery process.

A second group of vegetation communities can be characterized by high D values and medium-low A values (Figures 6 and 7). The high D value indicates that the areas can reach the "stability state" in a short time period, but this does not mean that the potential recovery capability is good, given that the A value is low (PF85 (sparse and dense shrubs)). In addition, the low B values show the variations caused by the fire are limited and the low recovery ability responds to the prefire conditions and the physiographic and physiologic constraints. However, in the dense shrub communities (Figure 7) when the high D values are joined at high B values, i.e. VE84 (dense shrubs), the great recovery process is related to the magnitude of the change caused by the fire.

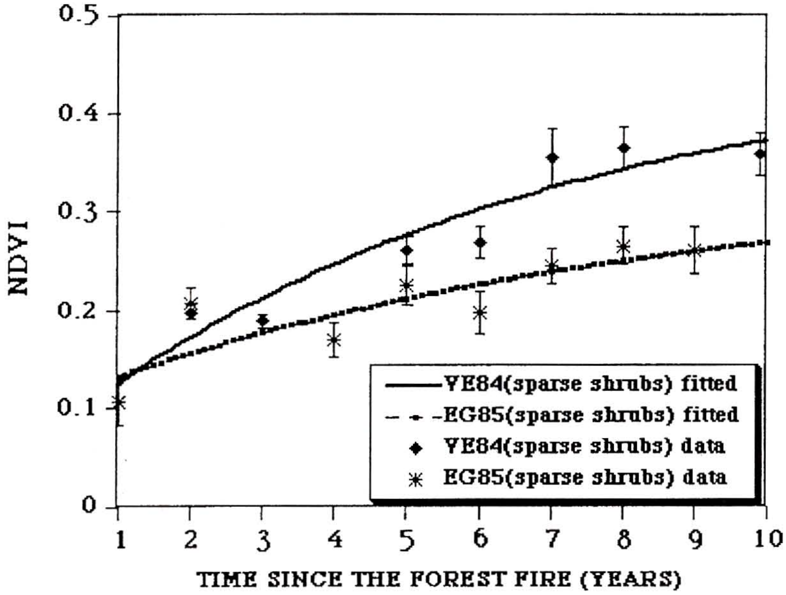
In the "tree shrubs" the high values for all constants analyzed (Figure 8) are noticeable and hence indicate adequate conditions to reach a full recovery process. However, we can observe how areas with greater damage intensity than others can recover faster and reach a stable condition. In Figure 8 the training areas have a similar NDVI value one year after the fire, although the magnitude of the change was greater in the VE85 (tree shrubs) than in PF85 (the B value is greater). The major recovery capability showed by VE85 is due to its better prefire conditions.

4. CONCLUSIONS

In the first place, it is necessary to emphasize the importance of the image normalization (topographic and atmospheric) to carry out any multitemporal study. In addition, when the aim of the study is to assess the vegetation behaviour, it is essential to take into account the phenological seasonal variations. In this work, some environmental parameters affecting the vegetation behaviour have been analyzed: the climatological conditions (rainfall), the degradation level of the vegetation community and the stoniness of the soils. However, a more precise treatment of these variables is necessary to accomplish the objectives.

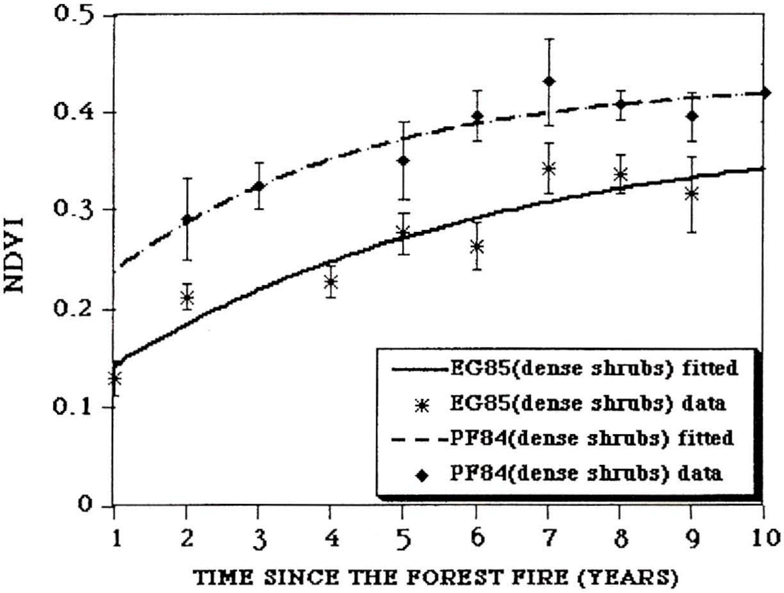
The mathematical adjustment provides parameters with an important ecological meaning for analyzing the regrowth processes after fires. In this sense, the constant A let us define the "potential recovery capability" of the communities. The constant B let us quantify the "magnitude of change" caused by the fire on the potential vegetation (A); the constant D is well related to the "stability speed" and indicates the temporal scale of the regeneration process, and finally the slopes of the curves express the "speed of recovery" of the burned communities. However, these constants only acquire sense when they are analysed simultaneously.

The model is appropriate for data with an exponential behaviour in their regenerative process. However, for data which are essentially linear, no asymptotically limiting value of A exists. In addition, this model is sensitive to some factors which must be controlled. For instance, different canopy configurations and soil reflectance, which play an important role with low ground cover. In this sense, and as a future work, a deep analysis of the several factors that characterize the complex variablity of the vegetation (phenological variations, clump distribution and variations in soil reflectance) will be necessary to correct the response obtained from the NDVI values.



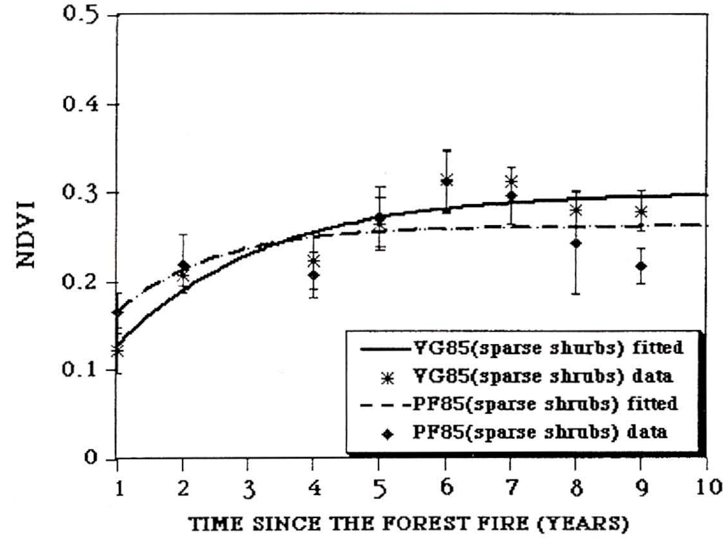
Training IDs	Vegetation Types	A	B	D	SLOPES AT DIFFERENT YEARS			
					1st	2nd	3rd	4th
EG85	sparse shrubs	0.34	0.23	0.12	0.025	0.022	0.019	0.017
VE84	sparse shrubs	0.45	0.38	0.15	0.051	0.043	0.037	0.031

Figure 4 - Near-linear recovery pathway on sparse shrubs communities. The bars represent ±1 standard deviation of the original mean NDVI values at each date.



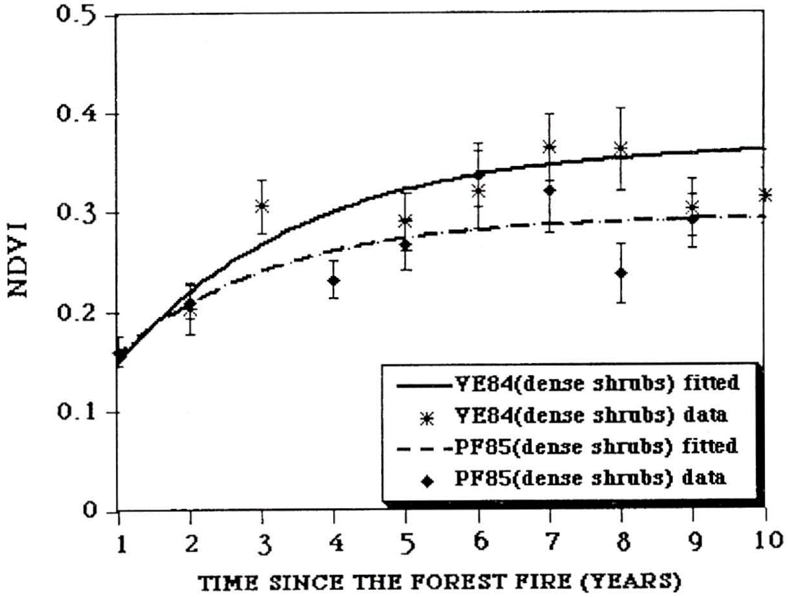
Training IDs	Vegetation Types	A	B	D	SLOPES AT DIFFRENT YEARS			
					1st	2nd	3rd	4th
EG85	dense shrubs	0.38	0.29	0.18	0.045	0.038	0.031	0.026
PF84	dense shrubs	0.43	0.26	0.29	0.057	0.042	0.031	0.026

Figure 5 - Near-linear recovery pathway on dense shrubs communities.



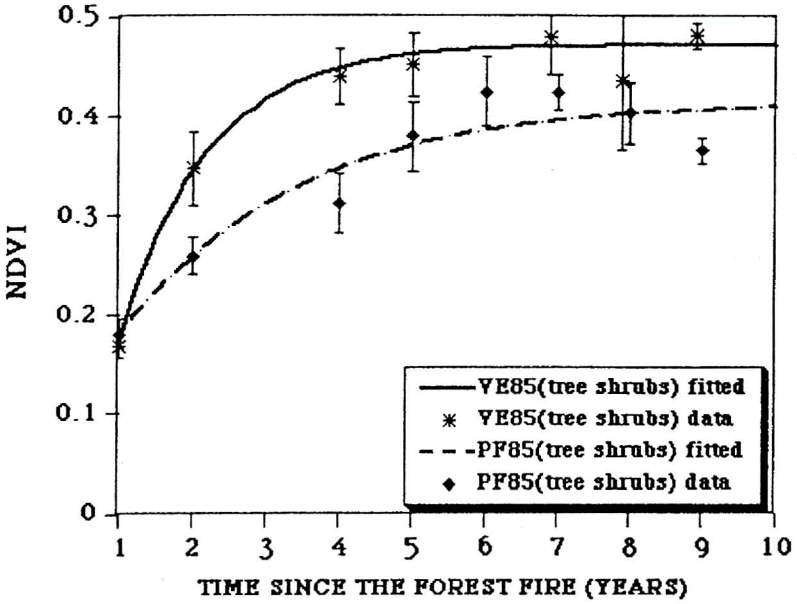
Training IDs	Vegetation Types	A	B	D	SLOPES AT DIFFERENT YEARS			
					1st	2nd	3rd	4th
VG85	sparse shrubs	0.31	0.27	0.45	0.078	0.049	0.031	0.021
PF85	sparse shrubs	0.26	0.19	0.68	0.066	0.033	0.017	0.008

Figure 6 - Exponential recovery pathway on sparse shrubs communities



Training IDs	Vegetation Types	A	B	D	SLOPES AT DIFFERENT YEARS			
					1st	2nd	3rd	4th
VE84	dense shrubs	0.34	0.81	0.76	0.287	0.134	0.063	0.029
PF85	dense shrubs	0.29	0.21	0.45	0.062	0.039	0.025	0.015

Figure 7 - Exponential recovery pathway on dense shrubs communities



Training IDs	Vegetation Types	A	B	D	SLOPES AT DIFFERENT YEARS			
					1^{st}	2^{nd}	3^{rd}	4^{th}
VE85	tree shrubs	0.47	0.71	0.85	0.260	0.111	0.046	0.019
PF85	tree shrubs	0.41	0.36	0.42	0.101	0.065	0.043	0.028

Figure 8 - Exponential recovery pathway on forested shrubs communities.

5. ACKNOWLEDGEMENTS

The work reported here was made possible through the collaboration and general support of some institutions and departments. Among them, we have to mention the following: the CEAM (Centro de Estudios Ambientales del Mediterraneo), the Centro Meteorologico Territorial de Valencia, the Conselleria de Medio Ambiente and the Departmento de Termodinamica of the University of Valencia and the Departmento de Ecologia of the University of Alicante.

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