# MULTITEMPORAL LANDSAT TM DATA FOR MONITORING THE EFFECTS OF FOREST FIRES AND VEGETATION RECOVERY PROCESSES IN MEDITERRANEAN AREAS

**Andrea PATRONO, Adriano BAPTISTA, Jan EBELTJES**
Western European Union Satellite Centre, Madrid, Spain
pat@weusc.es, bap@weusc.es, ebe@weusc.es

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## ABSTRACT

Evaluation of forest fire damage is an important issue in Mediterranean areas where the long arid season often creates favourable conditions for the occurrence of fires. Such fires are a major concern because of the environmental damage they cause. The objective of this study was to establish a methodology to detect and outline the extent of the damage caused by forest fires and to monitor the post-fire land recovery in Mediterranean-type vegetated areas. After experimenting and testing several techniques, a set of methods has been developed and assembled to provide an operational image processing flow for fire management. A set of study areas located in Greece and Turkey, heavily affected by fires in the last decade, has been used as test sites. Multi-temporal LANDSAT Thematic Mapper (TM) imagery was used to study the pre-fire situation, to delineate the immediate extent of the damage after the fire and to monitor and estimate the recovery of the vegetation. The study demonstrated that via the trend analysis of vegetation indices imagery derived from the visible and near infrared channels of TM (in particular the Normalized Difference Vegetation Index (NDVI)), it was possible to evaluate the health and rate of change, to monitor the speed of the growth and, with some limitations, to predict future growth of vegetation. Under certain constraints (time series, image availability, etc.), the methodology has proven reliable and repeatable in most of the considered situations, providing a practical solution for large area monitoring of post-fire situations and representing a key input for post-fire environmental management.

## 1 INTRODUCTION

### 1.1 Study Objectives

The first goal of the study was the recognition and exact delineation of areas affected by fire. Their geographical location is generally known but there may be a gap of information concerning the accurate definition of the extent and the intensity of the phenomenon (due to, e.g., problems of access in mountainous areas). For multi-temporal analysis, remotely sensed data offers a viable solution, especially if multi-spectral sensors are used (like LANDSAT TM). Once affected areas were identified, the study went through a set of steps to evaluate the environmental damage, to assess the health of the vegetation and to keep track of its recovery process.

The sequence of methods applied is the following: (a) evaluation of the effectiveness of different techniques for the identification and delineation of the areas affected by fires; (b) identification and classification (when feasible in terms of image availability and ground information) of the pre-fire land cover of affected areas; (c) monitoring of the recovery of vegetation; this phase was subdivided in several steps: NDVI analysis of affected areas (using post-fire multi-temporal data), identification of the areas characterised by common growth and modelling of the growth rates with best-fitting techniques; (d) comparison, by mean of cross-tabulation, between the land-cover, areas affected by fire and recovery results.

The study was designed to create output information and products that were optimised for decision makers involved in the fire management, e.g. to better establish and plan mitigation measures (like tree replanting) and systematic ground check for risk analysis, to evaluate the effectiveness of restoration activity implemented in the post-fire period. The management of fire affected areas is necessary and, of course, critical to avoid other natural hazards that affect and further degrade burnt areas (as an example, heavy soil exploitation and erosion may decrease slope stability and cause landslides). All analysed areas were mainly characterized by mediterranean forests - some fires also affected anthropic areas - for which fire has always constituted a serious threat. Although coastal pine forests, mountainous landscapes covered by fir, pine and beech trees and the degraded natural ecosystems of evergreen sclerophyl brush (e.g. maquis vegetation etc.) are well adapted to fires, frequent and repeated fires denude the vegetation from the land cover making necessary a whole set of mitigation measurements. Erosional problems may be exacerbated by subsequent overgrazing of burnt areas.

### 1.2 The Study Areas

A set of 16 test sites heavily affected by fires in the last decade was requested to be investigated by the Western European Union Satellite Centre. The analysed sites were principally located in the regions of Thessaloniki, Halkidiki, Attiki, Lakonia, Ilia and Arcadia in Greece and the regions of Gelibolu and Marmaris in Turkey. The analysed fire seasons covered a time range of 7 years, from 1992 to 1998; the available LANDSAT TM data set covered a time frame of 9 years from 1991 to 1999. The acquisition philosophy adopted for each fire, was to acquire a spring image pre-fire, an image immediately post-fire and all possible spring images post-fire (trying to match as much as possible the dates of acquisition). In the individual areas, the regions affected by fire varied from 1,000 to 8,300 ha.

## 2 METHODS

### 2.1 Burnt Areas Identification

Measurement of the surface area of vegetation burnt during fire events is a fundamental input required by environmental managers for estimating quantities of biomass burnt and for studying land change processes such as deforestation, soil erosion, etc. Spectral characteristics of burnt surfaces are dependent on the type of vegetation cover affected by fire, the soil characteristics and the time elapsed since burning occurred, leading to a wide range of spectral responses. Specifically, the spectral signature of a burnt area is influenced by two different aspects: the spectral characteristics of the combustion products and the spectral change due to the partial or complete removal of the pre-existing vegetation (Maselli *et al.*, 1996).

The TM sensor on board LANDSAT 4 and 5 provides useful information on the characteristics of burnt surfaces. The TM bands widths are optimised for vegetation discrimination. TM band 4 (near-infrared) is particularly useful to determine vegetation types, health, and biomass content. The methods used in this study are illustrated below; they are based on the use of spectral response of burnt areas at a given wavelength and on vegetation indices (see 2.3).

The methods used are the following: (a) the TM band 4 post-fire imagery, when stretched and filtered, delineates the loss of vegetation vigour, e.g. caused by the fire, generally highlighted with darker (gray) tones; (b) TM band 7, band 4 and band 1 (of post-fire imagery) in RGB colour composites provide in dark red tones a clear overview of the extent of fires; (c) multi-temporal RGB colour composites detect spectral changes; pre-fire and post-fire images are used to detect fire-related alterations (if available, three TM band 4 images, pre-fire, immediately post-fire and a third from a following year, may serve this purpose); NDVIs may be an excellent substitute for the use of TM band 4; (d) principal component transformations, a technique designed to analyse information content and distribution in multi-spectral data, were applied to images produced by merging pre- and post-fire imagery. The resulting principal components are oriented within the data such that areas that show high correlation, i.e. areas with similar DN values on each date, appear in the first component; areas that show low correlation, i.e. the areas that have been affected by fire, appear in the lower order components. Results of (a), (b), (c) and (d) had been enhanced combining them through logical and mathematical operation of masking and subtracting. Due to varying environmental conditions each method may have differing results and effectiveness, however, by combining them, they always fulfilled the objective of detecting all the fire affected sites, analysed in this study.

### 2.2 Land Cover Classification

Once areas affected by fire had been identified, the following objective of the study was to analyse, on pre-fire imagery, what had been burnt. This was necessary to study *a posteriori* the relation between the original vegetation coverage and the natural re-growth rates. Multi-spectral data were used to perform the classification using the spectral pattern present within the data for each pixel was used as numerical basis for categorization. First several classes of different combinations of digital values, based on their inherent spectral reflectance and emittance properties were recognized. Representative training samples had then to be identified and a numerical description of the spectral attributes of each land cover type has to be developed with the help of available land cover maps. Each pixel in the image data set was then categorized into the land cover class it most closely resembles using the Maximum Likelihood algorithm.

LANDSAT TM band 3, band 4 and band 5 (of the pre-fire images) had been selected in the study areas for the supervised classification. The selection of these bands was because of their spectral characteristics in relation to vegetation monitoring and detection, and the proportion of overall variance with the total data they represent. These LANDSAT TM band widths are finely tuned for vegetation discrimination: TM band 3 matches the chlorophyll absorption range that is important for discriminating vegetation types, TM band 4 is useful to determine vegetation types, health, and biomass content and TM band 5, in general, offers also a good contrast between vegetation types (Lillesand and Kiefer, 1987). Natural colour and false colour composites derived from TM bands 2, 3, 4, and 5 also provided help in the definition of the training samples.

### 2.3 Monitoring Vegetation Condition

The status of plant population is commonly measured or estimated in terms of plant cover (the proportion of the substrata covered) or biomass (the total weight of the living organisms). It is particularly informative because it provides an indication of the resources produced/consumed and the amount of physiological stress present. Various mathematical combinations of red (R) and near infrared (NIR) channels have been found to be good indicators of the presence and condition of vegetation/active green biomass (Sabins, 1987). These mathematical quantities are thus referred to as vegetation indices. The NDVI is a combination of addition, subtraction, and division of R and NIR channels; for the LANDSAT TM sensor the formula is the following:

$$NDVI = \frac{IR - R}{IR + R} = \frac{TM4 - TM3}{TM4 + TM3} \qquad (1)$$

Vegetated areas generally yield high values because of their relatively high near-infrared reflectance and low real reflectance. In contrast, water has larger visible reflectance than near infrared reflectance thus, such features yield negative index values. Rock and bare soil areas have similar reflectance in the two bands and result in a vegetation index near to zero. The normalized index is preferred to the simple index for multitemporal and/or global vegetation monitoring because it helps compensate for changing illumination conditions, surface slope, aspect, and other extraneous factors.

### 2.4 Modelling Vegetation Growth

After a damaging event such as fire, when an area becomes potentially available for vegetation recovery, plants tend to colonize in a series of temporary stages. Gradually, more permanent plant communities develop until a mature stage takes over reading equilibrium with the regional climate and the local substratum, topography, and water conditions (Odum, 1993; Whelan, 1995; De Bano *et al.*, 1998). Replanting can speed up the entire process. In post-fire analysis this is important for two main reasons: (1) the method presented here may be used for replanting feasibility studies or (2) for evaluating ongoing replanting strategies. Due to the temporal limitations of remotely sensed imagery, it is impossible to predict the time of full vegetation recovery - which can take several decades - but it is possible to monitor the first phases of recovery and activity (Fiorella and Ripple, 1993). Additionally, this is not applicable as a long term forecast since unpredictable natural or anthropogenic occurrences may easily modify the studied growth rate. In recent fires obviously no modelling was performed for lack of data. The entire methodological approach is summarized in the flow-chart of Figure 1.

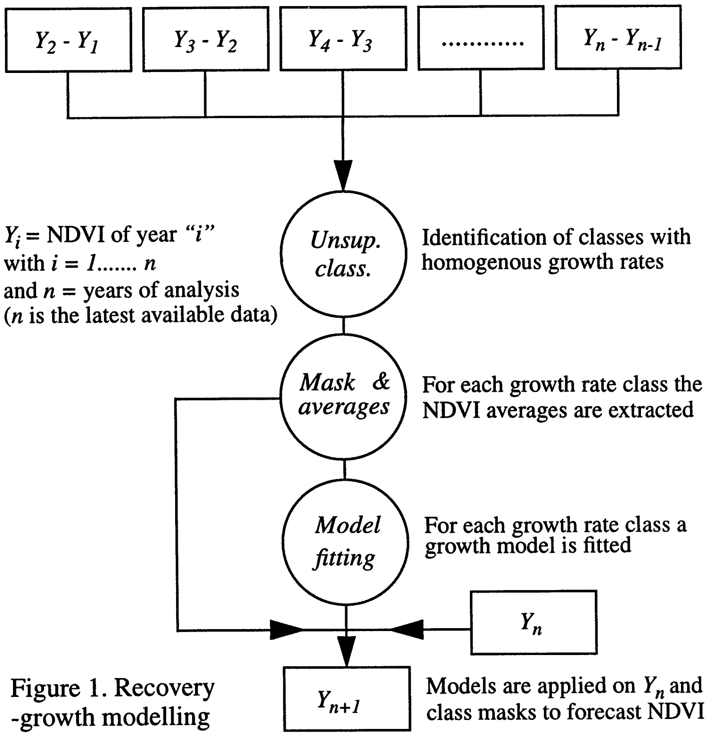

Figure 1. Recovery -growth modelling

NDVI images highlight active green biomass, which in a period of high biomass production can be correlated to the production activity itself. For this reason, differences between NDVI images of successive years were used to detect and monitor the post-fire recovery, year by year. The different images had then to be classified with an unsupervised statistical method to group and map areas delineating homogeneous growing rates (that is homogeneous differences of NDVI values). These results were then used to forecast future NDVI - biomass developments.

The following step was to find a solution to model the regrowth trends of the areas characterized by homogeneous growing rates of NDVI and this was done through best fitting procedures using polynomial functions of 3rd/4th order. The functions adequately simulate the vegetation recovery which is generally very rapid in the first/second year and then slows down. According to the data set available (necessary to compute the function parameters) and the R-squared results, one of the two following functions was used when feasible:

$$y = ax^3 + bx^2 + cx + d \tag{2}$$

$$y = ax^4 + bx^3 + cx^2 + dx + e \tag{3}$$

For each class, after the computation of the NDVI averages (year by year), a growth model was fitted, describing/characterizing the growth process of each homogeneous area. Using the latest available NDVI, it was then possible to forecast the future active biomass situation applicable to each mask representing a growth class. When feasible the model parameters were modified first eliminating the last NDVI reference available and then re-predicting it and, consequently, re-adjusting the model, and so on in a feed-back process, till the best fit was obtained.

## 3 RESULTS

### 3.1 Fire Identification and Land Cover Mapping

Considering the collateral data related to fire sites and the available satellite imagery, the entire set of 16 fire regions could be identified using one or more of the mentioned methods. The simplest solution for a first survey and recognition of the sites was the 7-4-1 TM band combination (of the immediate post-fire image) in RGB; once identified the area, a more detailed investigation, using for example the principle component analysis (see Figure 2), permitted more precise extraction of the affected areas. This process was followed by masking and raster-to-polygon operations to create an area of interest to focus the next part of the analysis.

Whereas the detection of fire-affected areas presented few complications, a detailed recognition and consequent classification of land cover classes was more complex particularly in the areas where appropriate maps/information about land coverage were not available; in the frame of giving priority to the operational use of remotely sensed imagery, no field work was planned for achieving the study objectives. Consequently, in the majority of the areas, the land classification was simplified to a discrimination of forests, shrubs and crops (with possible site by site implementations related to particular environmental conditions).

### 3.2 Monitoring and Modelling Vegetation Growth

The main result in terms of monitoring post-fire vegetation vigour/activity was that NDVI values, used for this purpose, generally reached pre-fire levels in an average of two/three years (see an example in Figure 3, (a)-(e)). Exceptions included cultivated or replanted areas - in this case anthropic activity governs the recovery - or, for example, re-burnt areas, detected in approximately 30% of the sites, further confirmation of the risk that the fire phenomenon represents in these environments.

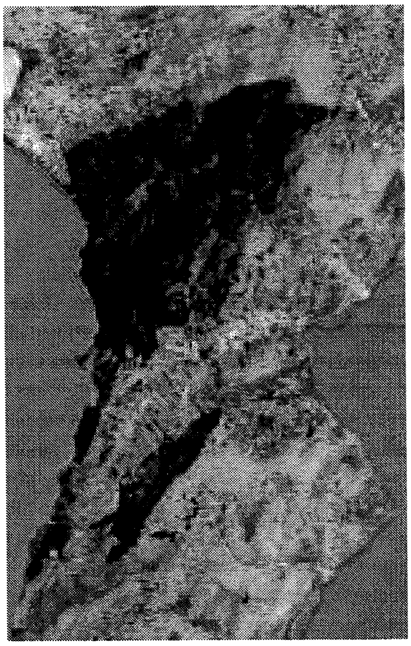

Figure 2. Second principal component of combined NDVI (pre/post-fire)

In all the areas where the number of images allowed to solve the modelling requirements, unsupervised classifications of

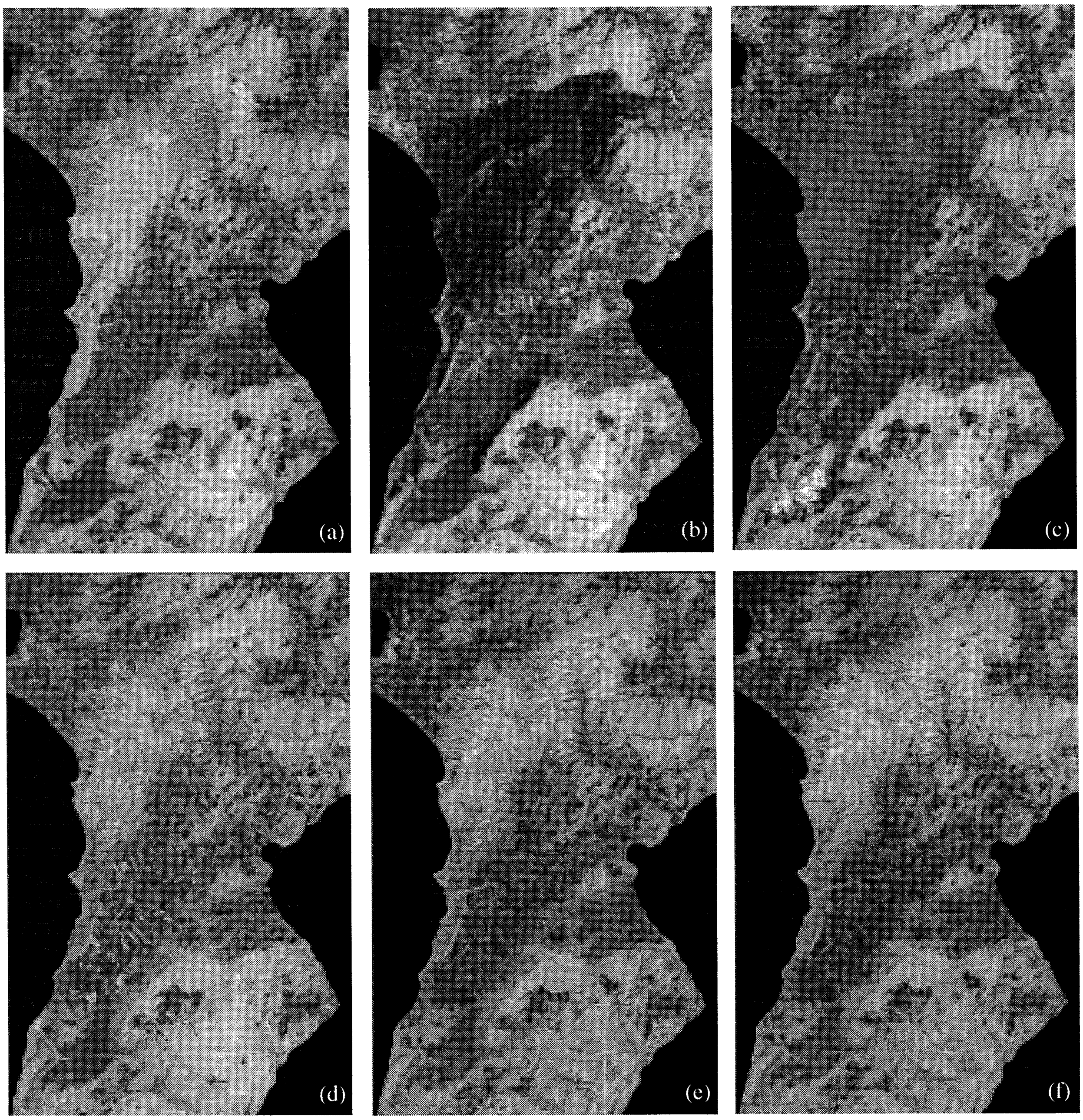

Figure 3. NDVI images: (a) pre-fire, (b) post-fire, (c)-(d)-(e) respectively 1-2-3 years after fire, (f) 4th predicted year

the NDVI differences had been computed to identify and group zones with homogeneous growth rates. When detected, anomalies, random variations, etc. in trends, which resulted in poor model fitting, highlighted situations previously mentioned, such as anthropic activities, recurrent fires, overgrazing, erosion, etc. or, in general, excessively spoiled/damaged plots. For the rest of the areas the modelling emphasized and confirmed the vegetation recovery (that is possible to quantify using the fitted NDVI curves) after the fire damage (see Figure 3 (f)). In some areas the calculated activity was higher than in the pre-fire situation, which is supports the ecological theory/expectation that the rates of production/activity are higher in full recovery phases than in equilibrium ones (where part of the effort is focused in maintaining the biomass). The results of the method were verified, wherever feasible, by collateral data (e.g. the correlation between known replanted areas and extrapolated NDVI trends).

## 4 CONCLUSIONS

The present NDVI interpreting/modelling approach, when supported by a sufficient multi-temporal data set, makes it possible to evaluate the initial phase of vegetation recovery processes in fire affected areas. In terms of forecasting full vegetation recovery, some limitations have to be mentioned: data availability for the present study covered a range of maximum 9 years; this means that only the first steps of the recovery could be effectively/efficiently modelled, such as ecological processes that can take decades depending on the intensity of the fire and the % damage. Additionally the long term forecast is not entirely acceptable and applicable since unpredictable natural or anthropogenic occurrences may easily modify the extrapolated trends.

Despite the fact that all sites are characterised by typical Mediterranean features, the methods applied have, in some localised cases, minor discrepancies and effectiveness due to locally varying environmental and climatic conditions; an addition of collateral data - for example land cover, terrain, climatic, etc. - would have helped in solving doubtful situations.

From a practical viewpoint, the developed methodology strives to lead the information output to a stage that can be of best use for decision makers involved in post-fire management. For example when replanting occurs within the imagery time frame (as in one of the studied cases) the efficiency of the methodology can be analysed in terms of deviation from the expected trend or, vice versa, the analytical process may be used to highlight areas characterized by lower recovery ratios (e.g. extremely damaged areas) where mitigation measurements should be enforced to avoid further deterioration.

As a general conclusion, it is possible to state that in most of the areas, affected by anthropic pressure and not in extreme environmental situations such as very steep slopes, the NDVI values reach the pre-fire levels in an average range of three/four years, confirming that the pioneer stages of vegetation recovery have an immediate post-fire reaction.

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