Burned area mapping and post-fire monitoring of a Mediterranean forest using NDVI time-series of low resolution imagery and the BFAST method

Mapeamento de área queimada e monitoramento pós-fogo de floresta na região Mediterrânea a partir de série temporais de imagens NDVI e do método BFAST

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Abstract

The Breaks For Additive Seasonal and Trend (BFAST) method was applied to NDVI composite series derived by MODIS and VEGETATION sensors in order to detect the rapid and gradual changes caused by fire in a typical Mediterranean ecosystem. This iterative approach identifies break points after decomposing time series into a trend, a seasonal and a noise component. The potential of this method was investigated for mapping a burned area and capturing the post-fire vegetation recovery trend and additionally assessment of the results from the analysis of the two datasets was performed. The spatial validation of the generated burned area maps revealed a better level of agreement for the MODIS NDVI derived perimeter compared to the VEGETATION outcome, but both results were considered quite promising. In addition, the post-fire vegetation trend was successfully captured from the analysis of these two datasets, although insufficient reference data did not permit a more thorough accuracy assessment. Still, the slope of the gradual changes observed in the trend component displayed post-fire vegetation recovery for both NDVI datasets.

Key words: burned area mapping; post-fire monitoring; remote sensing; time series analysis; NDVI

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Resumo

O método "*Breaks for Additive Seasonal and Trend*" - BFAST foi aplicado sobre uma série de imagens *NDVI* derivada dos sensores *MODIS* e do *Vegetation* com finalidade de detectar mudanças rápidas e graduais causadas pela ação do fogo num ecossistema mediterrânico típico. Essa abordagem iterativa identifica pontos de interrupções após a decomposição de séries temporais em uma tendência, uma sazonal e uma componente de ruído. O potencial deste método foi investigado para o mapeamento de uma área queimada, capturando a tendência de recuperação da vegetação pós-fogo e, adicionalmente, permitindo avaliar os resultados da análise dos dois conjuntos de dados temporais utilizados no presente estudo. A validação espacial dos mapas gerados sobre a área queimada revelou um melhor nível de concordância para o perímetro *NDVI/MODIS* comparado ao sensor *Vegetation*, mas ambos os resultados foram considerados bastante promissores. Além disso, a tendência de recuperação da vegetação pós-fogo foi capturado com sucesso a partir da análise dos dois conjuntos de dados-sensores, embora insuficientes dados de calibração temática não permitirem uma avaliação completa de melhor acurácia. Ainda assim, a inclinação que expressa as mudanças graduais observadas na componente de tendência mostra uma recuperação da vegetação pós-fogo em ambos os conjuntos da série de dados *NDVI*.

Palavras-chave: mapeamento de área queimada; monitoramento pós-fogo; sensoriamento remoto; análise de séries temporais; NDVI.

Introduction

Natural fires are an integral part of many terrestrial ecosystems and are considered as an important ecological process that is affecting the natural cycle of vegetation succession and the ecosystem's structure and ecological function, especially in fire prone environments like the Mediterranean region (PAUSAS, 2004; RIANO et al., 2007; CAPITAINO; CARCAILLET, 2008). Their impact is great on vegetation composition as they can cause the loss of protective vegetation cover (LENTILE et al., 2005) and alter the biological nutrient cycling (MENAUT et al., 1993), while they potentially contribute to soil erosion and degradation processes (THOMAS et al., 1999; PEREZ-CABELLO et al., 2006). Precise information about the extent and type of fire and also on the post-fire vegetation recovery is therefore required for the estimation of ecological and economic losses (GITAS et al., 2012). More specifically, the use of accurate post-fire impact information is considered essential for selecting the appropriate treatments to be applied (PATTERSON; YOOL, 1998), quantifying the fire impact on landscape (VAN WAGTENDONK et al., 2004) and planning and monitoring restoration activities (JAKUBAUSKAS et al., 1990); (GITAS, 1999).

In the past years, satellite remote sensing systems have provided the successful means for gathering valuable post-fire information in a time-saving and cost-effective way. Satellite data from systems with varying spatial and spectral characteristics have been extensively utilized in burned area mapping and monitoring studies, while an increasing number of developed methods and techniques have been implemented (PEREIRA et al., 1997; CHUVIECO et al., 2005; GITAS et al., 2008; VERAVERBEKE et al., 2012). On a long term basis, time series of satellite data can offer a better understanding of fire behaviour and contribute to the generation of historical fire data. Such extensive multi-temporal datasets have been mainly provided by coarse and medium resolution sensors, such as the Advanced Very High Resolution Radiometer (AVHRR), the Moderate Resolution Imaging Spectroradiometer (MODIS), and SPOT VEGETATION (VGT) and have been broadly used in burned area mapping and post-fire assessment studies (STROPPIANA et al., 2002; CHUVIECO et al., 2005; VAN LEEUWEN et al., 2010).

A plethora of change detection methods have been introduced with vegetation index differencing being one of the most frequently utilized in post-fire impact assessment. The Normalized Difference Vegetation Index (NDVI) has been traditionally utilized in such studies (GOETZ et al., 2006; CUEVAS-GONZÁLEZ et al., 2009) due to its strong relationship with above ground biomass. At the same time, a substantial percentage of these change detection studies are based on the use of a restricted number of images, which cover a specific season over different years (COPPIN et al., 2004). The main advantage of using low resolution datasets is their high temporal frequency which facilitates the generation of detailed time profiles and discrimination of fire induced changes from seasonal ones. However, although long series allow for the identification of rapid and gradual disturbances in the ecosystem, shorter series may lead to incorrect interpretations of phenological variations as actual changes (DE BEURS; HENEBRY, 2005). It should be also mentioned that in time series change analysis studies, regardless of the dataset length and frequency, specific thresholds are selected that may additionally cause confusion since thresholds are often subjective and scene-dependent (LU et al., 2004).

A recently introduced trend analysis method enables the analysis of long time series without having to select specific thresholds or time trajectories. The Breaks For Additive Seasonal and Trend (BFAST) method decomposes in an iterative manner time series into three main components, namely a trend, a seasonal and a noise one. This decomposition results in the detection of rapid and gradual phenological changes in ecosystems and facilitates also the discrimination of seasonal variations. BFAST has been introduced and successfully applied to MODIS NDVI series by Verbesselt et al. (2010) in change detection studies in Australian forest ecosystems.

In this work, the BFAST method is applied to NDVI composite series derived by MODIS and VEGETATION sensors in order to detect the rapid and gradual changes caused by fire in a typical Mediterranean ecosystem. The specific objectives were:

- to investigate the potential of BFAST approach for mapping a burned area and capturing the post-fire vegetation recovery trend in a Mediterranean ecosystem, and
- to apply BFAST to two datasets from high temporal frequency satellite systems with different spatial resolution, namely, MODIS and VEGETATION, and assess the accuracy of the results.

Study Area And Data

Study Area

The study area is located in North Greece in the southern part of the Kassandra peninsula and belongs to the prefecture of Chalkidiki. The Kassandra peninsula extends approximately from 25°25' to 25°35' East and 39°90' to 40°10' North and its area is estimated to be about 350 km^2. The elevation ranges from 0 to 335 meters above sea level with the area characterized by relatively low slopes and smooth relief. The climate is typically Mediterranean with mild winters and dry summers with the highest temperatures appearing from the middle of July until middle of August, which is also the period with the lowest precipitation. Pine forest is the main type of forest located in the Kassandra peninsula with *Pinus halepensis* being the dominant species, whereas the understory vegetation and shrubs mainly comprise the plant community of *maquis*. *Maquis* can be characterised as all the Mediterranean evergreen or deciduous broadleaves, mainly shrubs and young trees, which their height is not more than 2 meters.

From August 21st until August 25th of 2006 a major fire was burning in the Kassandra peninsula. The intensity and extent of the fire event caused the destruction of thousands of hectares of vegetated land, residences, and even caused casualties among civilians. Over one hundred residences and over one hundred vehicles were destroyed during the first two days of the fire event as it burned its way, with a front of approximately 20 km, through several residential areas. The development of multiple fronts, along with the great intensity of the winds blowing in the area, were the major factors that hindered the fire fighting efforts.

Data

In this work the following datasets were employed:

- MODIS surface reflectance composite products were acquired from the National Aeronautics and Space Administration (NASA) warehouse inventory search tool (WIST) (http://wist.echo.nasa.gov) for the period from 01/01/2004 to 31/12/2010, covering the northern Greek region. The MOD09Q1 (Surface Reflectance (SR) 8-Day L3 Global 250 m) products include the red and near-infrared spectral bands, at 250-meter resolution in an 8-day gridded level-3 product in the Sinusoidal projection. A Quality Assurance (QA) layer is also included that provides quality information about the product.
- VEGETATION D-10 composites were also acquired from the VITO site (http://free.vgt.vito.be/) for the period from 01/01/2004 to 31/12/2010. These are 10-day BDC syntheses or BiDirectional Composite syntheses with 1km spatial resolution, which are based on a bidirectional reflectance distribution function. The BDC Status Map (BSM) quality information is also included in the product.
- Reference data obtained from a validated classification and photo-interpretation of Landsat-5 TM satellite image covering the study site, that was captured during early September 2006.

Methodology

Data Preparation

MODIS raw data were initially imported and reprojected to WGS-84 Lat/Lon projection system, and were subset to include only the Kassandra study site. The QA information was used to further exclude from analysis low quality, as well as cloud affected and not atmospherically corrected pixels in the red and near-infrared bands. Importing of raw data and geographical subsetting was applied likewise to the VEGETATION composites. In addition, the BDC Status Map (BSM) quality information of the VGT composites was utilized in order to remove cloud affected and low quality pixels in the red, near-infrared bands. Afterwards, the processed red and near-infrared bands of the two sensors were used for the generation of the composite NDVI series for both datasets according to the equation:

$$NDVI = (\rho_{NIR} - \rho_{RED}) / (\rho_{NIR} + \rho_{RED}) \qquad (1)$$

where ρ_{NIR} and ρ_{RED} are the red and near-infrared reflectance, respectively. The Normalized Difference Vegetation Index (NDVI) is one of the most widely used indices in satellite remote sensing applications as it is strongly related to vegetation phenology and biophysical parameters, such as green cover, biomass, leaf area index and fraction of absorbed photosynthetically active radiation (TUCKER, 1979; BARET; GUYOT, 1991; CARLSON; RIPLEY, 1997).

The final step of the pre-processing activities was to create continuous NDVI time series by implementing a smoothing procedure, since the quality information of MODIS and VEGETATION datasets was not sufficient to totally remove atmospheric contamination effects or ensure the best radiometric quality. This was achieved by applying a second-order polynomial function, known as an adaptive Savitzky-Golay filter, that performs fitting of the data through a multi-step procedure (JONNSON; EKLUNDH, 2004). This fitting procedure, compared to other smoothing methods such as least-squares fitting, offers the advantage of facilitating the detection of sudden changes, which appear in satellite time series (VERAVERBEKE et al., 2010), although it is not recommended when extremely noisy data are involved.

The Breaks For Additive Seasonal and Trend (BFAST)

The Breaks For Additive Seasonal and Trend (BFAST) method, proposed by Verbesselt et al., (2010), decomposes time series in an iterative manner into three components, a trend, a seasonal and a noise one. This decomposition results in the detection of rapid and gradual changes that happen within the trend component or phenological changes occurring in the seasonal component. This is an additive decomposition model that iteratively fits a piecewise linear trend and seasonal model, given by the expression:

$$Y_t = T_t + S_t + e_t, \; t=1,\ldots, n \qquad (2)$$

where Y_t is the observed data at time t, T_t is the trend component, S_t is the seasonal component, and et is the remainder or noise component.

These changes are detected through the identification of break points resulting from the BFAST decomposition procedure. This iterative break point estimation has been initially introduced by Haywood and Randal, (2008), where they proposed the decomposition of time series into a piecewise linear trend and a constant seasonal pattern. This allowed for more flexibility when estimating structural changes as opposed to concurrent fits of the components where trend break points should appear at the same time with seasonal ones. In the BFAST approach, the presence of potential break points is investigated with the use of ordinary least squares (OLS) residuals-based MOving SUM (MOSUM) test and then the optimal number is assessed by minimizing the Bayesian Information Criterion (BIC) (ZEILEIS et al., 2003).

In this work BFAST was used for the analysis of the single NDVI series that were derived by MODIS and VEGETATION products for the period from 2004 to 2010. The implementation in the study area resulted in the identification of break points that revealed the time and range of all potential changes that occurred during the period of analysis. Detection of rapid disturbances within the seasonally adjusted (Yt - St) component were attributed to the fire event, while more gradual disturbance was mainly attributed to the post-fire vegetation trend. Before the BFAST analysis though, several settings of the algorithm had to be tested and selected, including the maximum number of breaks that would be estimated, the type of seasonal model used to fit the seasonal component, as well as the maximum number of iterations for the calculation of the break points. Finally, burned area maps were generated from the analysis of each NDVI dataset and were spatially validated against the reference data.

Results and Discussion

The BFAST was applied to the MODIS and VEGETATION NDVI datasets through a single series analysis and resulted in the identification of the statistically significant break points indicating all the changes that occurred during the time period examined. The break points revealed the time and range of the rapid changes within the trend component, which were caused by the fire in August 2006 and the burned area maps were generated for each processed NDVI dataset (Figure 1). The fire caused a sharp decrease in the NDVI values, followed by a gradual increase indicating potential recovery of vegetation over time. The positive post-fire trend is shown by the slope of the gradual change also observed within the trend component (Figure 2). It should be mentioned that for the analysis it was assumed that no other major change would occur and surpass the fire disturbance during the time of study.

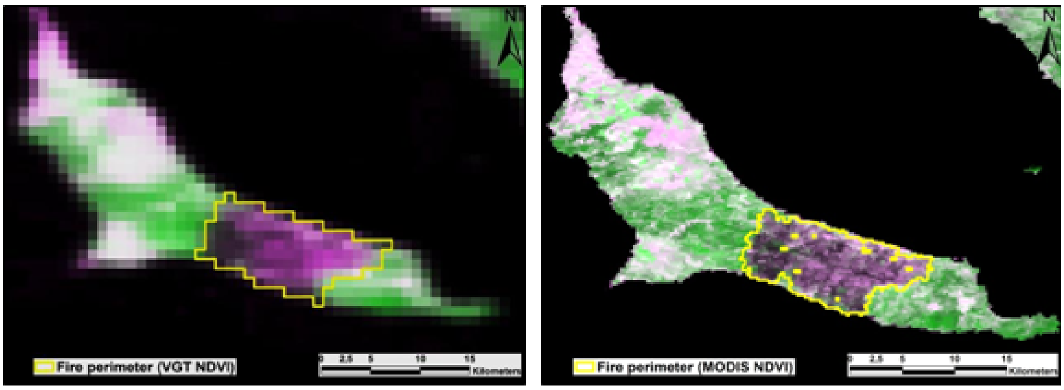

Figure 1. Derived fire perimeters by the BFAST implementation to: (left) VEGETATION and, (right) MODIS NDVI series at the Kassandra study area

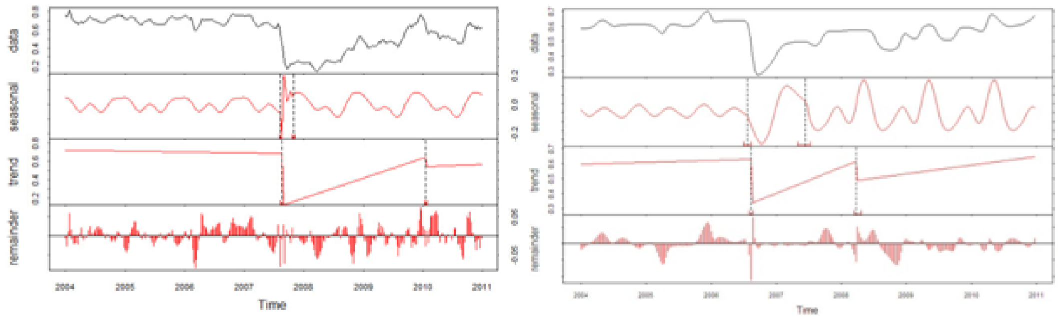

Figure 2. Seasonal, trend and remainder fitted components of the MODIS (left) and VEGETATION (right) NDVI series derived from a single pixel in a conifer forest of the study area. Dash lines (- - -) display the time of observed changes (break points) in the components and confidence intervals are also exhibited for each break point.

The NDVI decomposed series are graphically presented in figure 2, where the trend, seasonal and noise component plots are indicative of the BFAST fitting process. The decomposition plots are derived by a single pixel of MODIS and VEGETATION datasets within the pine forest of the study area. Depending on the vegetation type the inclination of the post-fire trend line may vary, nevertheless the time of the rapid change is identified in the trend component for every land category and the observed gradual change shows in general a positive increase in NDVI values. Also, for every break point a confidence interval is estimated by the model that determines the statistical significance of the corresponding change.

The generated fire perimeters from the BFAST analysis were spatially compared with the validated perimeter that was extracted by the Landsat TM scene captured after the fire. The comparison revealed an 89.6% level of spatial agreement regarding the analysis of MODIS NDVI series, while for the VEGETATION one a 78.5% level of agreement was achieved. It seems clear that the higher spatial resolution of MODIS compared to VEGETATION sensor yielded a more precise estimation of the burned area. Regarding the post-fire trend, lack of sufficient reference data did not allow for a solid and thorough validation of the results or for a comparison of the two sensors. Still, the vegetation recovery level appears to be satisfactory as derived from the analysis of both datasets, although the post-fire period is relatively short, namely four years until 2010. This can be attributed to the immediate vegetation succession, mainly shrub communities, which is common after fires in Mediterranean landscapes.

Conclusions

This paper presented the implementation of a modern trend analysis method which decomposes satellite time series iteratively and enables a non-simultaneous fit of trend and seasonal changes. The Breaks For Additive Seasonal and Trend (BFAST) method was utilized for the detection of the rapid and gradual changes that occurred in a Mediterranean ecosystem after a fire event. NDVI composite series derived by MODIS and VEGETATION sensors were analysed and resulted in the mapping of the burned area and capturing the post-fire vegetation trend. The spatial validation of the generated maps revealed a better level of agreement for the MODIS derived perimeter, which can be attributed mainly to the higher spatial resolution of the sensor compared to the coarse resolution of VEGETATION. Still, both results can be considered quite satisfactory.

In regard to the post-fire trend estimation, lack of sufficient reference data did not permit a robust and detailed accuracy estimation, however the slope of the gradual changes observed in the trend component displayed post-fire vegetation recovery for both NDVI datasets. In terms of future work, further adjustment of the BFAST settings and closer examination of the confidence intervals of changes can potentially yield improved results. Moreover, despite the fact that BFAST provides the time, number and range of changes, one should combine this information in order to characterize the type of disturbance, otherwise misleading results could be yielded.

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