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Detection and mapping of burnt areas from time series of MODIS-derived NDVI data in a Mediterranean region.

Research Article

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Abstract: Moderate resolution remote sensing data, as provided by MODIS, can be used to detect and map active or past wildfires from daily records of suitable combinations of reflectance bands. The objective of the present work was to develop and test simple algorithms and variations for automatic or semiautomatic detection of burnt areas from time series data of MODIS biweekly vegetation indices for a Mediterranean region. MODIS-derived NDVI 250m time series data for the Valencia region, East Spain, were subjected to a two-step process for the detection of candidate burnt areas, and the results compared with available fire event records from the Valencia Regional Government. For each pixel and date in the data series, a model was fitted to both the previous and posterior time series data. Combining drops between two consecutive points and 1-year average drops, we used discrepancies or jumps between the *pre* and *post* models to identify seed pixels, and then delimitated fire scars for each potential wildfire using an extension algorithm from the seed pixels. The resulting maps of the detected burnt areas showed a very good agreement with the perimeters registered in the database of fire records used as reference. Overall accuracies and indices of agreement were very high, and omission and commission errors were similar or lower than in previous studies that used automatic or semiautomatic fire scar detection based on remote sensing. This supports the effectiveness of the method for detecting and mapping burnt areas in the Mediterranean region.

Keywords: Burnt area mapping • Mediterranean Basin • MODIS-NDVI • Remote sensing • wildfire

1. Introduction

Wildfires are common and natural disturbances in Mediterranean climate zones worldwide, where they

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largely contribute to shape the structure and functioning of flammable ecosystems [1]. Thus, many Mediterranean species have acquired adaptive mechanisms to persist and regenerate after wildfires, facilitating the autosuccession of the plant community and contributing to accelerate the recovery of the vegetation cover [1, 2]. However, depending on fire attributes such as the severity, frequency or size, wildfires may promote critical changes in Mediterranean ecosystems and landscapes. For example, in the Mediterranean Basin, frequent wildfires maintain the dominance of shrubs in areas where the climate and soil conditions would be suitable for a forest ecotype [3–5]. Severe and/or frequent wildfires may also promote structural changes towards more fire-prone vegetation [6, 7]. Furthermore, the synergistic effect of wildfire and post-fire extreme climatic events, such as droughts or torrential rainfall, may result in long windows of disturbance, and challenge the resilience of Mediterranean ecosystems [8, 9].

During the twentieth century, the fire regime in the Mediterranean Basin has shifted to larger and more frequent wildfires [6, 10]. For example, in eastern Spain, a major shift around the early 1970s, resulted in annual fire frequency doubling with the average fire size four times larger for the post-1970s period than compared with the previous 100 years [11]. The main driving factor for this change was the rapid increase in fuel availability and continuity due to the combined effect of agricultural land abandonment and extensive reforestation programs [6, 11]. The rapid pace of these changes in fire regimes explains the growing concern about the future spatiotemporal dynamics and the associated ecological and socio-economic impacts of wildfires in the Mediterranean Basin, particularly under a climate change context that could imply a further increase in fire risk and frequency in the Mediterranean Basin [12, 13].

Accurate mapping of burnt areas as a result of wildfires are essential to analyze the spatiotemporal distribution of wildfires and its relation to different environmental factors, as well as to monitor the recovery of vegetation and the effect of management and restoration treatments. Fire scars can be mapped confidently from visual comparison of pre- and post-fire high resolution aerial photographs or satellite imagery of the zone that includes the wildfire. The resulting burnt area maps are widely used to investigate the spatiotemporal patterns of wildfire impacts [14–19]. Remote sensing from MODIS and other space-borne sensors has been increasingly used in the last decade for automatic or semiautomatic detection of active or past wildfires, usually from daily records of a suitable combination of reflectance bands, and with varying results in terms of accuracy, omission and commission errors [14, 20–30].

The objective of the present work was to develop and test simple algorithms and variations for automatic or semiautomatic detection of burnt areas from MODIS 250m biweekly NDVI time series data for a Mediterranean region. We evaluated the detection and mapping method on a target area located in the Valencia region, East Spain, which respresented a good model for most of the western Mediterranean Basin [11].

2. Methods

2.1. Data

MODIS data was downloaded from the NASA website (currently accessed through the Reverb data gateway, http://reverb.echo.nasa.gov/reverb/). We used the NDVI 16-day composite band from a time series of MOD13Q1 MODIS/Terra product at 250m resolution (tile h17v05), starting in February 2000.
A database of fire event records for the time period 2000-2005 was provided by the Fire Prevention, Extinction and Emergencies Office of the Valencia Regional Government (Dirección general de Prevención, Extinción de Incendios y Emergencias, Conselleria de Gobernación y Justicia, Generalitat Valenciana). For each fire event, the database included information on the date, name (municipality where the wildfire started), forest and total affected areas and the cartography of the fire perimeter, which was obtained from IRS or SPOT images and field surveys.

2.2. Burnt area detection and mapping

We used a two-phase algorithm to detect and map burnt areas, first detecting a subset of seed pixels showing significant drops, as described below, in the series of NDVI data, and then delimitating the fire scar for each potential wildfire using an extension algorithm from the seed pixels. The main steps of the detection and mapping method used in this work are described as follows (see Table 1 for the corresponding pseudocode, and [31] for a description of the steps of the algorithm illustrated with examples):
For each individual pixel in the area, all points in the time series of NDVI data were considered as potential change points, i.e., potential dates of wildfire occurrence. Separate models were fitted to the data before and after the change point (hereafter *pre* and *post* models), and the discrepancies between the models were computed.
A number of different types of models were tested, such as polynomials of different degrees and models including cyclic terms. Discrepancies between the parameters of the *pre* and *post* models were used as measure of the magnitude of the jump in NDVI values at the potential

change-point. An efficient algorithm was devised for equispaced data such as nominal dates in NDVI biweekly series. The algorithm was valid for a wide family of fitting models for which discrepancies between parameters of the fitted models were linear functions of the data. In this way, similar to Savitzky-Golay smoothing method [32], the parameters could be computed with an appropriate digital filter as the convolution of the vector of data with a suitable vector of weights. As a result of a wide set of trials, the complex models were discarded and a combination of two simple models was selected: a simple constant model of 1-year amplitude to account for the dominance of an annual phenological cycle of the vegetation, and the difference between two consecutive points. Discrepancies between *pre* and *post* models were calculated using the product of two Haar wavelets of amplitude n+n and 1+1, also known as a travelling Haar pulse.

For each pixel in the area, the value of the detected maximum drop in the series of NDVI values was calculated; a map of smoothed maximum drops using a Gaussian kernel of short amplitude was obtained, and a few NDVI curves were selected, corresponding to individual pixels in the proximity of the local maxima in the map, as the curves with maximum real non-smoothed change in NDVI values in a very reduced neighbourhood of the local maxima. The selected curves were ranked by the magnitude of their maximum NDVI change, and only those with drops exceeding a certain threshold were retained as seed pixels for the second phase of the method. In this work, the threshold was set to a value of 0.13, derived from visual exploration of a subset of potential large wildfires.

From the set of seed pixels, an extension clustering algorithm was applied to define spatially contiguous clusters through some measure of similarity between each pixel in the region and those used as seeds. A simple effective approach consisted of clustering spatially contiguous pixels with detected maximum drops in NDVI values corresponding to dates similar to those of the seed curves, or by using a combination of dates closeness and curves similarity, measured as the correlation between their temporal series, or curves, of NDVI values.

2.3. Evaluation of the method

We evaluated the detection and mapping method against the regional database of fire event records of the Valencia region. We compared the burnt areas detected by our method with the registered wildfire perimeters and burnt area, for the time period 2000-2005 in a region of interest (ROI) in the Valencia region, located on the Mediterranean east coast of the Iberian Peninsula (Figure 1). The ROI is a large area of 10.178 km^2, including the central part, and 44% of the total area, of the Valencia region. For the period 2000-2005, and considering a minimum fire size of either 15 ha or 90 ha, the total burnt area in the ROI was more than 62% of total burnt area for the whole Valencia region (Table 2). We compared the maps of detected and registered burnt areas using the GIS system ESRI® ArcGis 9.0 (Environmental System Research Institute Inc., California). From this comparison, we estimated the confusion matrices for the sets of detected and registered fires with areas larger than 15 ha and 90 ha, and computed overall accuracies, omission and commission errors, and several indices of agreement [33, 34].

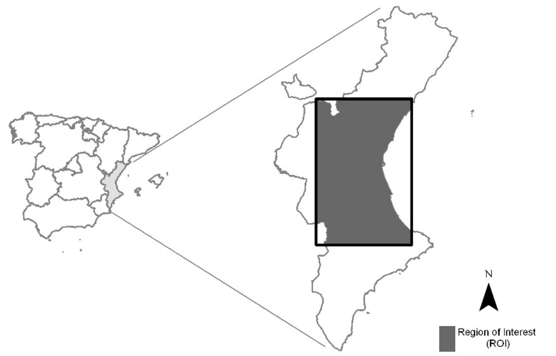

Figure 1. Location of the Region of Interest (ROI) in the Valencia region, East Spain.

3. Results

The application of the method to the ROI, using the combination of local and 1-year average drops to define seed pixels, yielded the results shown in Figure 2 (only detected fire scars with areas larger than 15 ha are mapped). Table 3 shows the confusion matrices that resulted from the comparisons between detected fire scars and the reference perimeters registered in the official, regional database. A set of accuracy measures estimated from the confusion matrices is presented in Table 4. Values of overall accuracy and the various indices of agreements were very high, particularly for the subset of medium-to-large (>90 ha) detected burnt areas as compared with the whole set (>15 ha) of detected scars. Omission errors were very low, less than 4% for fire scars larger than 90 ha, while commission errors were moderately low. The accuracy of the method for the assessment of burned surface is illustrated in Figure 3. Either for large wildfires, such as the Chiva wildfire, or small ones, such as the Vall de Ebo wildfire, the agreement between registered perimeters and detected fire scars was very high. Table 5 compares the

Table 1. Pseudocode for the main steps of the algorithm for detection of burnt areas.

Input data: Time series of NDVI values for $nx \times ny$ pixels and nt temporal sections
Selection of seed pixels
- For each pixel $p \in nx \times ny$
  - Compute vector of drops in 1 year averages, $Hy(p)$, as the Haar transform with amplitude n+n (n=23)
  - Compute vector of local drops between consecutive temporal sections, $Hl(p)$, as the Haar transform with amplitude 1+1
  - Compute Haar pulse as the point product $H(p) = Hy(p) \times Hl(p)$
  - Find $Peak(p) = \max(H(p))$ and time $t_m(p)$ where it is attained
- Compute $SPeak(p)$, map of smoothed maximum drops with a Gaussian kernel
- Find $LMSPeak(p)$, local maxima in $SPeak(p)$
- Find a few pixels in the proximity of $LMSPeak(p)$ with maximum $Peak(p)$
- Select as seeds pixels, sp, those with $Peak(p) > Threshold$

Extension from seed pixels to connected areas (region growth algorithm)
- For each seed pixel sp
  - If sp is not already in a connected area
    - Initialize a connected region with seed pixel sp
    - Grow connected region by adding (to it) adjacent pixels that pass a similarity condition with the seed pixel
    - Stop when no more pixels are incorporated into the current region

Table 2. Number of fires and total and forest burnt areas in the ROI and the whole Valencia region, for the time period 2000-2005, for wildfires with affected areas exceeding 15 ha and 90 ha.

	ROI		Valencia region	
	Burnt area >15 ha	Burnt area >90 ha	Burnt area >15 ha	Burnt area >90 ha
Number of fires	52	18	77	31
Total burnt area (ha)	11130	10011	17862	16189
Forest area (%)	21	20	26	25

registered and detected burnt areas for each individual wildfire (>90 ha) in the ROI for the period 2000-2005. Overlapping areas ranged from 78.89 to 99.09 % (average value: 93.9 ± 1.1) of the reference registered area, with larger overlapping fractions for larger wildfires. Except for one case, the Jérica wildfire, the detected fire scar was slightly larger than the reference registered area.

4. Discussion

A wide range of Mediterranean burnt areas, ranging in size between 15 ha and 2500 ha, and including contrasting fractions of forest and non-forest regions(shrublands, grasslands, croplands) can be effectively detected and mapped with a simple two-phase algorithm for automatic detection of burnt areas from MODIS 250m biweekly NDVI time series data. In terms of overall accuracies, omission and commission errors and indices of agreement, the results obtained with our method were at a minimum, as accurate as previous studies which used a variety of automatic or semiautomatic fire scar detection methods from remote sensing in the Mediterranean Basin and other regions (see, e.g., [14, 29, 35–38] and references therein).

Some methods to detect fire scars from remotely sensed time series data incorporate, as is the case with our method, two different phases: first detecting possible abrupt changes in the temporal data for some pixels, usually by jointly considering several spectral indices, and then using some algorithm for region growing to finally delimitate the perimeter of the fire scar. This two-phase approach is a way of balancing or compensating omission and commission errors. Setting strict thresholds or conditions for a pixel to be selected as a seed for the second phase lowers commission errors. Then, omission errors are reduced by using, explicitly or implicitly, lower requirements to incorporate additional pixels in the extension phase [35–37].

In our method, detection of abrupt changes in NDVI as a consequence of vegetation burning was best achieved

Table 3. Confusion matrices from the comparisons of detected burnt areas with the Regional database of fire event records used as reference. Values represent total number of pixels.

Reference	Detected			
	Detected burnt areas >15 ha		Detected burnt areas >90 ha	
	Burnt	Unburnt	Burnt	Unburnt
Burnt	1837	240	1802	64
Unburnt	677	186884	416	187358

Table 4. Accuracy measures for detected burnt areas, larger than 15 ha and larger than 90 ha, as compared with the Regional database of fire event records used as reference.

	Detected burnt areas >15 ha	Detected burnt areas >90 ha
Overall accuracy (%)	99.52	99.75
Quantity disagreement (%)	0.23	0.19
Allocation disagreement (%)	0.25	0.07
Omission error (%)	11.55	3.43
Commission error (%)	26.93	18.76
Standard Kappa index of agreement ($k_{standard}$)	0.798	0.881
Kappa for no information (k_{no})	0.990	0.995
Kappa for allocation ($k_{allocation}$)	0.883	0.965
Kappa for quantity ($k_{quantity}$)	0.995	0.996

Table 5. Main characteristics of the registered (Regional database of fire event records) and detected (this study) burnt areas for wildfires with affected area larger than 90 ha recorded in the ROI for the period 2000-2005.

		Registered burnt area (R)		Detected burnt area (D)	
Date	Wildfire	Total burnt area (ha)	Forest area (%)	Total burnt area (ha)	D-R overlap area (%)†
16/09/2000	Chiva	2164.46	18.4	2508.41	99.09
28/08/2003	Buñol	1701.64	8.0	1974.55	98.37
03/09/2000	Simat de Valldigna	1259.13	25.5	1381.84	97.59
12/07/2005	Simat de Valldigna	641.95	12.1	792.55	97.92
12/08/2004	Serra	624.39	44.7	674.61	95.92
27/08/2000	Planes	558.42	16.2	639.17	97.74
09/08/2001	Vall de Gallinera	457.11	4.5	586.60	95.41
31/07/2000	Alcalalí	413.45	44.9	444.31	96.55
22/06/2005	Xativa	400.00	33.3	418.88	92.85
31/01/2003	Eslida	391.37	56.7	614.89	91.69
25/06/2001	Villalonga	275.05	0.4	293.44	96.30
24/01/2005	Vall de Almonacid	249.92	30.0	264.01	93.81
21/08/2000	Jérica	208.71	60.0	196.30	78.89
03/08/2000	Requena	190.76	50.0	214.87	91.86
29/08/2001	Chiva	174.30	3.4	199.84	95.34
11/10/2002	Beniganim	105.32	10.3	121.15	90.81
15/02/2005	Llaurí	99.13	9.1	115.15	90.13
27/08/2000	Vall de Ebo	96.16	8.4	98.29	89.40

† Overlapping of registered and detected burnt areas as percentage of the registered areas

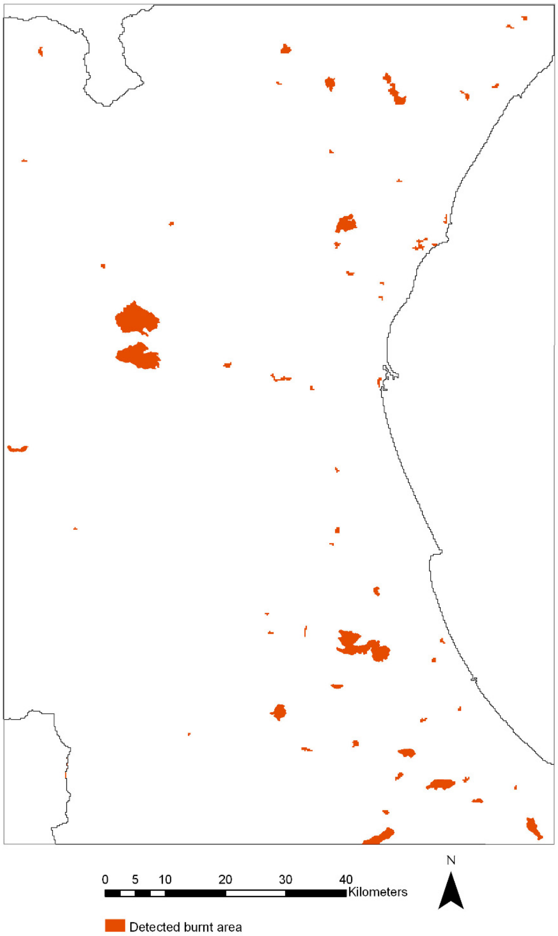

Figure 2. Detected fire scars (> 15 ha) from MODIS in the ROI for the period 2000-2005.

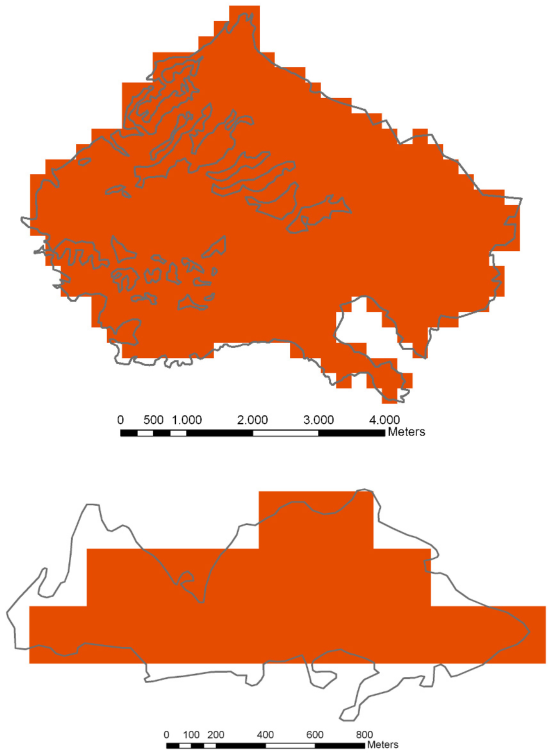

Figure 3. Registered perimeters (Regional database of fire event records) and detected burnt areas from MODIS (this study) for the largest (Chiva wildfire, upper panel) and smallest (Vall de Ebo wildfire, bottom panel) burnt area (>90 ha) recorded in the ROI for the period 2000-2005.

by using the product of the jumps in 1-year averages and the drops in NDVI values of two consecutive points, with no clear improvement by fitting more complex models to the pre- and post- partial data series. Local decreases between two consecutive values are normally used in different detection methods, although the use of 1-year averages has also been incorporated in some algorithms [39]. We found a clear improvement when using the combination of both differences, in comparison with the use of each of them separately. Both local drops in NDVI and substantial drops in pre- and post- 1-year averages may be produced by many factors different of fire, as local fluctuations in NDVI measurements, droughts and other climatic variations, agriculture and forest management, among others. However, their combination is likely to be the result of a wildfire.

In the second phase, delimitation of fire scars was based on propagating clusters from the seed pixels to spatially connected pixels with similarities between their dates of detected maximum drops and the correlations between their NDVI data series. The maps of the detected burnt areas showed a good agreement with the perimeters recorded in the database of fire events records used as reference, at least for medium-to-large fires, with affected area exceeding 90 ha. For this set of fires, the average percentage of burnt area detected by our method was very high (≈94%), with an average percentage of overestimation of 14.0 ± 3.1, which was mainly due to the low spatial resolution of the MODIS data. It is considered that our method can therefore equally be applied to higher resolution data, such as Landsat images, from which the expected results would improve. The method could also be used in a semiautomatic way, to analyse a window area where a wildfire is known to have occurred, in order to automatically delimitate its perimeter. It could also be fine-tuned by adjusting the value of the threshold to select the seeds, the amplitude of the filter used to compute the map of smoothed maximum drops, and the relative weights of the similarities in nominal dates of fire and correlations between NDVI curves in the clustering algorithm used to extent the seeds to the local characteristics of the area.

Although the evaluation of the algorithm was carried out over a relatively large area, it was applied using a fixed threshold value which should be adapted to the particular region to be analysed. As in other methods, the selection of the threshold value can be based on the distribution of detected maximum drops, or it may be derived from cross-validation from a set of independently mapped fire scars.

As the objective of the work was to test the ability of using MODIS-derived NDVI and simple methods to detect and map burnt areas, no other spectral band or indices were used, no systematic procedure to optimize the parameters of the method was performed, and no previous filtering of the evaluated area to discard agricultural or non-forest areas was applied. This left room for further improvements in the accuracy of the method.

5. Conclusions

In a large area in the Mediterranean Valencia region, for the temporal period analyzed burnt areas as a consequence of wildfires were efficiently detected from 250 m resolution MODIS derived NDVI 16-days time series data. A two-phase algorithm, first identifying seed pixels with maximum NDVI drops above some threshold, by combining local and 1-year average drops, and then clustering contiguous pixels with an extension algorithm provided good results. The maps of the detected burnt areas larger than 90 ha showed a good agreement with the perimeters registered in the database of fire records used as reference.

The algorithms of the method can therefore be efficiently implemented, allowing its application to large regions, and providing a useful tool for assessing ecological and environmental factors of wildfire patterns and impacts. Further work could extend the applicability of the method, by including the automatic selection of thresholds in NDVI jumps to facilitate its use in regions with different types of vegetation, and optimizing the modifications needed to best map areas with fire recurrence.

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