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Fire regime and post-fire Normalized Difference Vegetation Index changes in the eastern Iberian peninsula (Mediterranean basin)

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Abstract. Fire occurrence in Mediterranean landscapes has been studied widely. Despite this, a specific monitoring of vegetation recovery after recurrent fires by means of satellite images has been developed to a lesser extent. With the use of Satellite Remote Sensing (SRS) techniques and multi-temporal Landsat images of the area of Ayora (287 700 ha) in Valencia (Eastern Spain), between the years 1984 and 1999, we studied the post-fire regeneration of the Normalized Difference Vegetation Index (NDVI) in areas subjected to different fire recurrences. Emphasis is given to the effect of time since fire, precipitation, and bedrock types on post-fire NDVI changes. Results suggest that for the first 7 years after a single fire, NDVI depends mainly on the time since fire (post-fire regeneration), whereas environmental parameters (precipitation and bedrock type) are of little relevance. After this period, precipitation begins to have a direct influence on the NDVI. In patches burned twice, with fire intervals of 8 and 9 years, NDVI is also controlled by the time since fire. Furthermore, NDVI recovery is faster after the first fire than after the second fire, suggesting that fire recurrence has a negative impact on the resilience of these communities. Bedrock type did not show any effect on NDVI after fire. These findings contribute to the understanding of Mediterranean landscape dynamics and provide evidence for the usefulness of NDVI in post-fire regeneration assessment, and the possible negative effects of the increasing fire recurrences observed in the last decades.

Additional keywords: bedrock type; fire recurrences; forest fire; post-fire regeneration; precipitation; remote sensing.

Introduction

Fire is an ancient, universal phenomenon that has played an important role in creating many of the world's landscapes (Bond *et al.* 2005). In recent years, the fundamental role fire plays in maintaining ecosystem function has been recognised, leading to subsequent concern about the consequences of human impact on the natural cycle of wildfire disturbance (White *et al.* 1997; Thonicke *et al.* 2001). Monitoring post-fire regeneration is necessary for land management and soil erosion control (Cerdà 1998; Keeley 2000; Martin and Mooney 2001; Ruíz-Gallardo *et al.* 2004).

Given the very broad spatial extension, and often-limited accessibility of the areas affected by fire, there is a need for using geographic information systems (GIS) and satellite remote sensing (SRS) techniques, both of which are considered essential for gathering and analysing spatially explicit information (Chuvieco 1999; Pereira *et al.* 1999).

In the case of wildland fires, SRS-obtained time-series satellite images from before and after a fire can be introduced into the GIS to estimate fire severity (Chuvieco *et al.* 1997; Koutsias and Karteris 2000; Ruíz-Gallardo *et al.* 2004), and monitor vegetation recovery through time over large regions. Accurate methods serving this purpose are the vegetation indices that provide information on the state of the land cover (Baeza *et al.* 1998; Justice and Lorontzi 2001; Díaz-Delgado *et al.* 2002; Gilabert *et al.* 2002; Mitri and Gitas 2002). For instance, the spectral response of the vegetative communities after a fire can be monitored and modelled through the variations in the Normalized Difference Vegetation Index (NDVI) by determining the different levels of regeneration as a function of the environmental characteristics of the affected area (Fiorella and Ripple 1993; Díaz-Delgado *et al.* 1998; Henry and Hope 1998; Kushla and Ripple 1998). After wildfires, NDVI values drop spontaneously due to the loss of green vegetation. This can be observed clearly in the different wavelengths of visible and near-infrared sunlight reflected by the plants (Chuvieco *et al.* 2005). The NDVI is a reasonable proxy for the amount of green biomass, independent of the plant species. The NDVI has proved to be a key identifier for the dynamics of vegetation structure and function

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(Jia *et al.* 2002; Riaño *et al.* 2002), and it has become the most widely used tool for assessing the vegetation recovery process after a fire at the landscape scale (Viedma *et al.* 1997; Díaz-Delgado *et al.* 1998; Kushla and Ripple 1998; Viedma and Meliá 1999). One drawback of the use of NDVI for post-fire assessment is the tendency for commission error caused by changes in its value, which are not related to fire (Kasischke *et al.* 1995; Fraser *et al.* 2000) but to other factors, such as changes in weather conditions.

Our first hypothesis was that the NDVI regeneration rate in an ecosystem subjected to recurrent fires would depend on the inter-fire interval. Previous field studies suggested different plant regeneration rates in different bedrock types (Pausas *et al.* 1999); thus, our second hypothesis was that regeneration at landscape scale, as measured by NDVI, would also be affected by the bedrock type. We tested these hypotheses by monitoring NDVI changes in areas with different fire histories using multi-temporal-scale satellite images from the eastern Iberian Peninsula, and then related the NDVI values to post-fire time, precipitation, and bedrock type.

Methods

Study area

The present study was developed in the area of Ayora, located in the south-western part of the province of Valencia (eastern Iberian Peninsula) (Fig. 1). The area is delimited by the UTM coordinates SE (657, 4301), NW (714, 4356) of zone 30S north and covers an area of ~287 700 ha. Agricultural lands cover ~32% of the study area and wildlands (shrublands and forests) cover the rest.

In general terms, the study area is characterized by a Mediterranean climate, with mean annual temperatures ranging between 8 and 19°C, and with hot and dry summers. The mean annual precipitation ranges between 300 and ~650 mm. The annual precipitation regime is strongly bimodal, with precipitation concentrated in spring and autumn (>60%) and with dry summers (<20% of the annual precipitation) (Pausas *et al.* 1999). The very scant precipitation during the summer season is responsible for long dry periods with a high fire risk (Pausas 2004), mainly between the months of July and September.

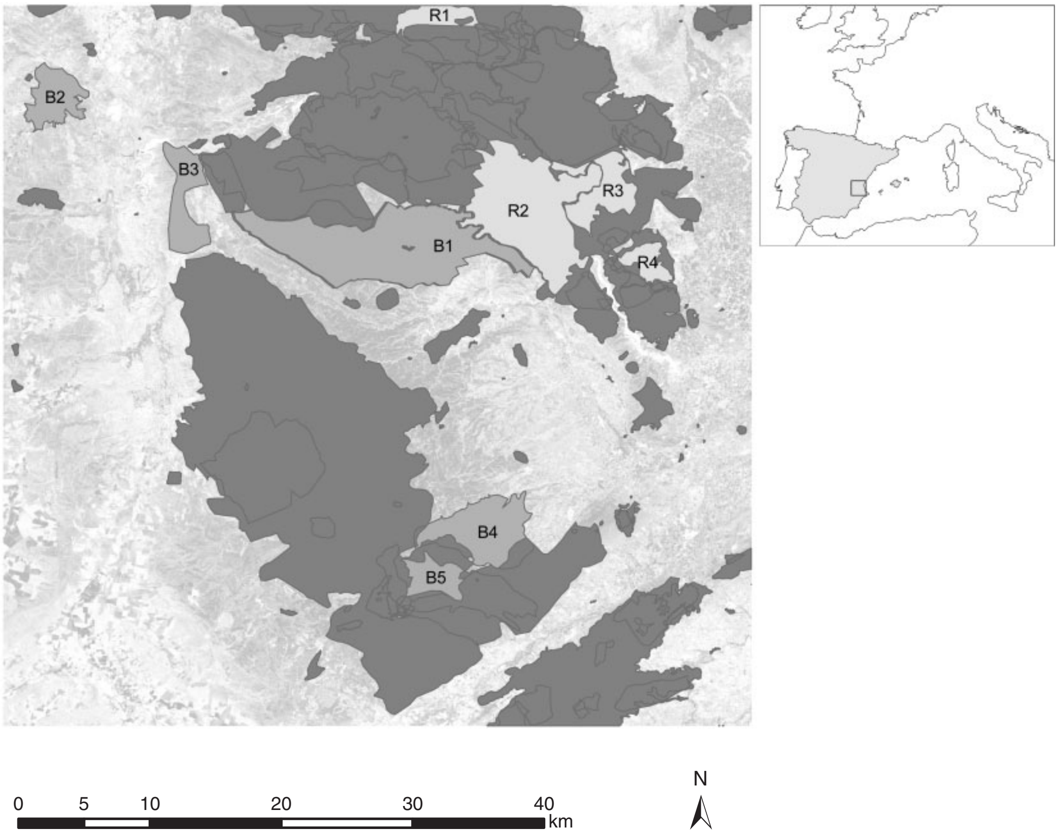
The region is typical of a Mediterranean fire-prone ecosystem and most of the plants have the ability to regenerate after fire (Trabaud 1992; Pausas *et al.* 1999, 2004*a*). The main vegetation types are evergreen shrublands (garrigues and heathlands with varying abundance of *Quercus coccifera*, kermes oak) and pine woodlands (*Pinus halepensis*, Aleppo pine), often with abundant *Cistus* spp., *Ulex parviflorus* (gorse) and *Brachypodium retusum* (Costa 1999; Pausas *et al.* 1999). Two main bedrock types are present in the study area: limestone, which is calcareous hard rocks that produce shallow and decarbonated red soils with abundant cracks; and marls, which produce uncracked deeper and highly carbonated soils (Vallejo and Alloza 1998). In addition, other less abundant bedrock types (conglomerates, sandstones, schists) or mixed marls and limestone types may also occur in the study area.

Analysis

The wildland fires that occurred in the study area from 1978 to 2000 (inclusive) were digitised at the 1 : 50 000 scale and then introduced into a GIS system, along with a multi-temporal series of Landsat images. The wildland fire data were acquired from the local Valencia government as perimeters drawn on 1 : 50 000 topographic maps of the whole province. The source of the data used to monitor NDVI was a set of nine remotely sensed images of the area of Ayora, corresponding to Landsat 5 TM (raster format) from the following years: 1984, 1985, 1986, 1989, 1991, 1993, 1994, 1996, and 1999. All the images were taken between April and July, which is close to the time when maximum plant activity is expected. The resolution of the Landsat images was 30 m × 30 m (pixel size). The images had been geometrically corrected for earth curvature and cubic convolution re-sampling by means of a Digital Elevation Model. They had also been radiometrically calibrated to include a topography correction. In addition, the data were georeferenced (geometrically registered) to one another at identified control points. All these image corrections were made by the University of Trier (Germany). The calculation of the NDVI was computed for all the corrected satellite images. The fire boundaries acquired from the paper maps were also corrected using the abrupt changes in the NDVI from the pre- and post-fire remote sensing images. In order to avoid confusing low NDVI values due to wildland fires with other causative factors, a mask was applied on the non-forest areas, including agricultural areas and freshwater bodies (Abdel Malak 2003).

The study area was divided into patches according to fire history. First, we selected all the forest land that was unburnt during the study period to analyse the NDVI variability that could not be attributed to fire occurrence but rather to climatic variability. Second, we selected patches that had been burned once, to monitor post-fire regeneration and its relation with climatic variability. In this case we compared the vegetation regeneration after each of the fires by calculating their mean NDVI values. Finally, we selected patches that had suffered two fires during the study period in order to study the effect of fire recurrence on NDVI regeneration. Post-fire NDVI changes had been studied for the first 7 years and for the whole available period. Nine patches fulfilled our criteria of having been burned in a period that enabled the analysis of several post-fire years, and of having an area large enough for the study. Four of these had burned twice during the study period. The size of these patches ranged between 650 and 8600 ha (Fig. 1).

The fire cycle, which is the time it takes to burn an area equal in size to the study area (Johnson 1992), was calculated from the available data on number and size of the wildland



Legend
Burned patches

▨ Burned once
▨ Burned twice
☐ Other burned patches (1978–2000)

Fire ID	Fire size	Times burned	Date of first fire	Date of fire recurrence
B1	8648	1	1985	
B2	1458	1	1984	
B3	1661	1	1985	
B4	3184	1	1991	
B5	1009	1	1984	
R1	864	2	1983	1991
R2	6422	2	1985	1994
R3	1760	2	1985	1993
R4	697	2	1984	1992

Fig. 1. Localization of the study area in the western Mediterranean basin (*right*). A satellite image of the study area (Ayora) showing the perimeters of the five studied patches burned once (B), the four studied patches burned twice (R), and the other burned patches not studied (*left*); the remaining area was unburned during the study period.

fires. Mean fire interval was calculated as the mean of different fire intervals for all the patches burned more than once.

Rainfall data were obtained from ten meteorological stations around the studied patches. The mean precipitation values were calculated for the 6 months prior to the image taking to see if any relation existed between yearly vegetation changes and precipitation. This precipitation data (winter and spring) was considered to be directly involved in the vegetation condition up to the date of the image taking. All patches studied were divided according to the major bedrock types present in the study area, which are limestone, marls, and others, and based on the digital geological map (1 : 50 000) of the Valencia region. NDVI regeneration after fire was compared for the different bedrock types. ANOVA was used to validate the significance of the relationships between the NDVI and the independent variables (rainfall, bedrock type, and post-fire successional time).

The use of NDVI as an indicator of plant regeneration has some limitations that need to be mentioned. NDVI levels reach a threshold, or saturation level, before the maximum biomass is reached. In the present study, this may not be of major importance because the vegetation requires several years to recuperate, i.e. to reach its maximum level, and this study focuses on calculating the NDVI values only a few years after fire.

Results

Fire statistics

Fifty-six percent of the whole study area had been subjected to at least one fire during the study period (23 years), and up to three recurrent fires have been observed for this period. From the area affected by fire, 64% burned only once, 34% burned twice, and 2% burned three times. There were a total of 130 fires, ranging from less than 1 ha up to 38 900 ha with a total cumulative burned area of 208 100 ha. The fire cycle calculated for the study period was 22 years. The yearly burned area ranged from 70 to 51 800 ha, with a mean value of ~8500 ha (5.3% of the forest area) and a standard deviation of 14 700 ha (Fig. 2).

Unburned areas

On average, NDVI values for the unburned forest showed some inter-annual variability with time. Part of this variability can be explained by the amount of precipitation during the 6 months previous to the satellite images ($R^2 = 0.538$, Fig. 3).

Areas burned once

Normalized Difference Vegetation Index changes in the areas that were burned once during the study period were studied for a period of 15 years after fire. NDVI values after fire show a significant increase with time (Fig. 4*a*). This increasing pattern is stronger during the first 7 years after fire than during the total period (Fig. 4*a*), suggesting a tendency toward community senescence after this age. This behaviour was also reported in pine regeneration studies carried out in north-eastern Spain (Díaz-Delgado *et al.* 2002). NDVI variability for the whole period was mainly related to both precipitation and successional changes (Table 1). However, during the first 7 post-fire years, the effect of rainfall was negligible (not significant) compared to the importance of post-fire successional time (Table 1). In no case was bedrock type significant.

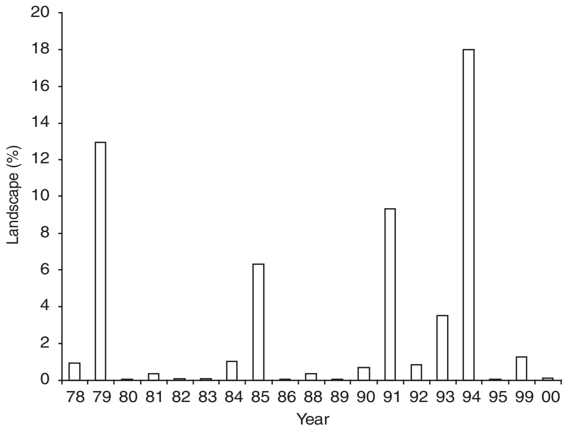


Fig. 2. Proportion of the landscape burned annually during the study period. Missing years are years without any fire.

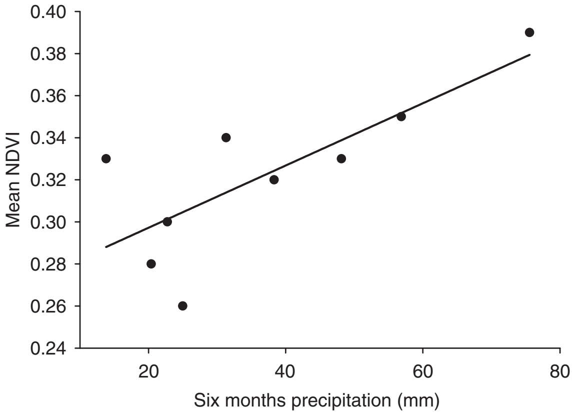


Fig. 3. Relationship between Normalized Difference Vegetation Index (NDVI) values for the unburnt area during the years in which satellite images were available, and the January–June precipitation calculated from the 10 meteorological stations in the study area that had complete precipitation data for the 1984–1999 period. The relationship between the 6-month precipitation and the NDVI values is significant ($R^2 = 0.538$, $P = 0.024$).

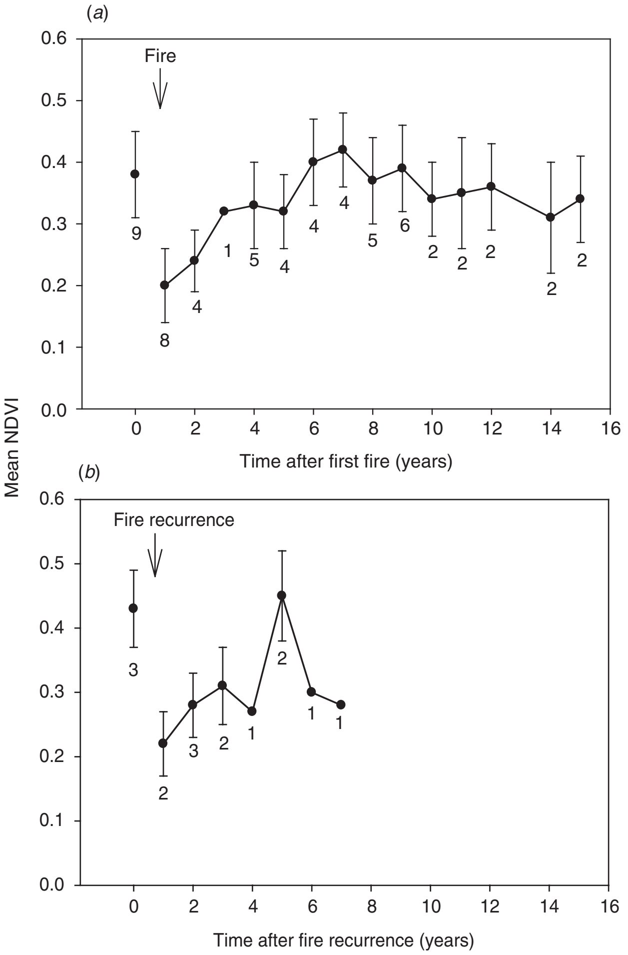


Fig. 4. Normalized Difference Vegetation Index (NDVI) regeneration in nine forest patches following the first fire (*a*) and in four forest patches following the second fire (*b*). The standard deviations are shown as vertical lines and indicate the variability between patches. Arrows indicate the first (*a*) and the second (*b*) fire. The numbers under the mean NDVI values correspond to the number of patches considered for the calculation of the mean NDVI.

Areas burned twice

The NDVI recovery of the four patches that had sustained two recurrent fires with inter-fire periods of 8 and 9 years was studied (Fig. 4*b*). Post-fire successional time was strongly and positively related to NDVI values (Table 2). The fact that the interaction between fire (first or second) and time (Table 2) was significant suggests that NDVI recovery is significantly different between the first and the second fire, being lower after the second fire (Fig. 4). In these patches NDVI changes did not show any relation to bedrock types.

Discussion

For the period ranging from 1978 to 2000, 130 wildland fires were characterized in the area of Ayora (287 700 ha). These fires affected 56% of the landscape. A large percentage of the landscape had been subjected to more than one fire (~20%) during the 23 years studied. Our data revealed that the fire cycle in the study period (~22 years) can be considered high compared to studies carried out in the California counties, where the fire cycle is estimated to range between 29 and 81 years, depending on the zone (Keeley *et al.* 1999). Our analysis suggests that the average forest area burned per year amounts to ~5.2% of the total forest area, and that the mean fire interval calculated for the patches subjected to fire recurrences in this system is about 9 years. This average value is considered short compared to studies done on other Mediterranean forests with fire return intervals ranging from 10 to 60 years (Thonicke *et al.* 2001), as well as other ecosystems like the Oregon Cascades with an average value of 9 to 42 years (Mcneil and Zobel 1980; Agee 1993), and Sierra Nevada, California with an average value of 9 to 18 years (Kilgore and Taylor 1979).

Inter-annual rainfall variability was shown to affect NDVI values in non-burnt areas (Fig. 3) and in the areas burned more than 7 years ago (Table 1). In these cases, NDVI was seen to be positively related to the precipitation, as has been shown in other dry ecosystems (Davenport and Nicholson 1989; Bonifacio *et al.* 1993; Farrar *et al.* 1995; Prosper-Laget *et al.* 1998; Wang *et al.* 2003). During the 7-year period following the first fire, time since fire (post-fire succession) seemed to be the only studied factor that affected the NDVI regeneration. Neither precipitation nor bedrock type seemed to influence this relationship significantly during this post-fire period (Table 1). In contrast to field studies at plot scale (Pausas *et al.* 1999), bedrock type did not show any significant effect on landscape regeneration during the post-fire period (Tables 1 and 2). This may be due to topographic heterogeneity at landscape scale, compared to the units used when working at plot scale, or to the different temporal scales studied.

Normalized Difference Vegetation Index regeneration analysis of the patches burned twice demonstrated a slower recovery in the second fire when separated from the first by an interval of 8 to 9 years. This result is observed even though the NDVI value of the first year following the first fire was lower than this value following the second fire, which may be due to lower fire intensity in the second fire (due, in turn, to the low fuel accumulation during the short fire interval). Thus, even after a lower intensity fire, vegetation tends to recover more slowly after a second fire. The lower recovery rate after the second fire could be due to lower resprouting success after recurrent disturbances (Canadell *et al.* 1991; Delitti *et al.* 2005), to the reduction in the number of fast-growing or seeder plants (Trabaud and Lepart 1980; Díaz-Delgado *et al.* 2002), or to the local disappearance of the dominant tree, *Pinus halepensis*. The regeneration of the dominant tree in the study area, *Pinus halepensis* (Pausas *et al.* 2004*c*), depends on the fire recurrence. If the fire-free period (fire interval) is shorter than the age at which these trees reach maturity (~6 to 10 years), the species will be locally eliminated (Zedler *et al.* 1983; Pausas *et al.* 1999; Vilà *et al.* 2001). Because there is no permanent soil seed bank for pines, the tree stratum loses its auto-regeneration capacity after repeated short fire intervals (Zedler *et al.* 1983; Pausas 1999).

As a consequence of the lower regeneration, areas with recurrent fires may be more susceptible to soil erosion and desertification (Vallejo and Alloza 1998), affecting the species vegetation composition, the structure of the

Table 1. ANOVA results for the effect of time since fire, precipitation and bedrock on Normalized Difference Vegetation Index regeneration after the first fire for the whole period (15 years after fire) and for the first 7 years after fire

Source of variation	d.f.	*F*	*P*
Whole period (1–15 years)			
Time (since fire)	1	33.32	$<0.00001^{****}$
Precipitation	1	46.72	$<0.00001^{****}$
Bedrock (limestone, marls, others)	2	0.770	0.465^{ns}
Residuals	108		
First 7 post-fire years			
Time (since fire)	1	108.43	$<0.00001^{****}$
Precipitation	1	0.026	0.873^{ns}
Bedrock (limestone, marls, others)	2	0.674	0.514^{ns}
Residuals	59		

^{ns}Not significant; ****$P < 0.0001$.

Table 2. ANOVA results for the effect of time since fire, bedrock and recurrence on Normalized Difference Vegetation Index regeneration after the second fire (twice-burned patches) for the 7 post-fire years

Bedrock type has only two classes as none of these patches were on marls

Source of variation	d.f.	*F*	*P*
Time (since fire)	1	39.06	$<0.00001^{****}$
Fire (first *v.* second)	1	0.056	0.814^{ns}
Bedrock (limestone, others)	1	0.0001	0.991^{ns}
Time × fire	1	6.27	0.0176^{*}
Residuals	32		

^{ns}Not significant; *$P < 0.05$; ****$P < 0.0001$.

ecosystems, the availability of soil nutrients, and the local hydrology (Justice *et al.* 1993). The vegetation occurring in these zones may need priority in restoration planning in order to lower the risks of desertification or local extinction of some plants (Pausas *et al.* 2004*b*).

The Landsat images available for calculating the NDVI were, in general, close to the maximum annual NDVI values because most images were taken during the maximum plant activity (spring). However, at least two images (1986 and 1989) were taken in July and showed lower values than expected (i.e. comparing to the observed seasonal variation for these years in coarser scale images; analysis not shown). The values of these two images contributed to the estimation of the post-fire NDVI regeneration after the first fire during the first 7 years only (Fig. 4*a*), and thus lowering their corresponding mean NDVI in Fig. 4*a*. This reinforces our result, as appropriate NDVI values would provably increase the differences between once- and twice-burned patches (Fig. 4*a* and *b* respectively; Table 2).

The NDVI index utilized in this work does not distinguish between different vegetation types, although, as mentioned above, it does provide good monitoring of green biomass. The latter is the basic element used when decisions need to be taken in forest management and planning, even though, as addressed by other researchers (Milne 1986), knowledge of vegetation types and conditions is necessary for a better understanding and interpretation of the nature of the wildland fire damage. The variability of NDVI regeneration within and between patches may be due to the topographic variability, which was not considered in the present study. The use of slope and elevation models (Pardo *et al.* 2001) could further improve the predictability of NDVI changes.

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