Fire Recurrence and the Dynamics of the Enhanced Vegetation Index in a Mediterranean Ecosystem

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ABSTRACT

This study area is located in the eastern littoral of the Iberian Peninsula; its importance resides in its Mediterranean ecosystem, complex topography, extensive land use changes, and intensive forest fires history. The study is done at the landscape level, covering a wide area for an extended period of time. This work uses Geographic Information Systems (GIS) and Satellite Remote Sensing (SRS) techniques to evaluate the impact of spatio-temporal parameters on shaping Mediterranean landscapes. Interacting ecological parameters are analysed and correlated to post-fire vegetation regeneration in an attempt to understand its dynamics. The results provide evidence that the number of fires separated by short time intervals influence vegetation growth negatively measured as Enhanced Vegetation Index (EVI). During this period, micro-climatic effects (soil and environmental humidity) are major factors influencing EVI-measured vegetation regeneration. The conclusions expect shifts in Mediterranean plant communities in heavily burned ecosystems stressing the importance of their correct short and long term post-fire management.

Keywords: *Enhanced Vegetation Index (EVI), Fire Recurrences, Forest Fires, Geographic Information Systems (GIS), Mediterranean Ecosystem, Remote Sensing, Topography, Vegetation Regeneration*

1. INTRODUCTION

Repeated disturbances alter landscape structure and can lead to ecosystem deterioration when disturbance regime is outside the natural range (Johnston & Gutsell, 1994). In Mediterranean ecosystems, landscape patterns proved to affect ecological processes including spread of

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disturbances, particularly fire (Alloza & Vallejo, 2006). In north-western Mediterranean region, forests are currently facing an increasing risk of wildfires due to inappropriate management, policies violations and agriculture abandonment.

It is widely admitted that vegetation has developed different mechanisms to recover its structure and composition rapidly after forest fires in Mediterranean ecosystems (Buhk et al., 2005). However, plants are not adapted to fire *per se*, but to fire regimes (Pausas & Keeley, 2009), and many current fire regimes in the Mediterranean Basin are outside the natural (historic) ranges. Fires, by concentrating in specific places, and by becoming more frequent in already burned areas could increase fire disturbance modifying the landscape. At least in Spain, increasing forest fire tendencies in terms of numbers and burned areas during last decades lead to a shift in the nature of burned areas where forests are replaced by non-wooded shrublands (Moreno et al., 1998).

These facts are leading ecologists to establish a better understanding of ecosystem functioning at the regional scale and of changes in fire regime as key steps towards an enhanced characterization of post-fire ecosystem resilience ability in the Mediterranean landscape (Oliveira & Fernandes, 2009). Though they possess some limitations, Geographical Information Systems (GIS) and satellite remote sensing (SRS) techniques are a potential instrument for ecologists in their ecosystem analysis and monitoring (Chuvieco et al., 2006) especially over large geographical extents. Using these techniques, recent research suggests that fire occurrence in the Mediterranean has increased both in frequency and intensity leading to negative impact on plant communities' resilience (Abdel Malak & Pausas, 2006). Furthermore, a number of limitations in the ecosystem recovering abilities are highlighted at the population and the landscape levels depending on fire frequency, intensity, severity and on topo-climatic conditions have also been highlighted (Moretti et al., 2010; Rodrigo et al., 2004).

This study bases on these outcomes and takes research further by asking whether fire recurrence is the only driving force affecting vegetation, or whether other ecological parameters need to be taken into consideration when planning post-fire management interventions. It aims at understanding long term effects of intensive forest fires and topo-climatic characteristics on large western Mediterranean ecosystems characterised by their complex geography through multi-temporal and spatial analysis.

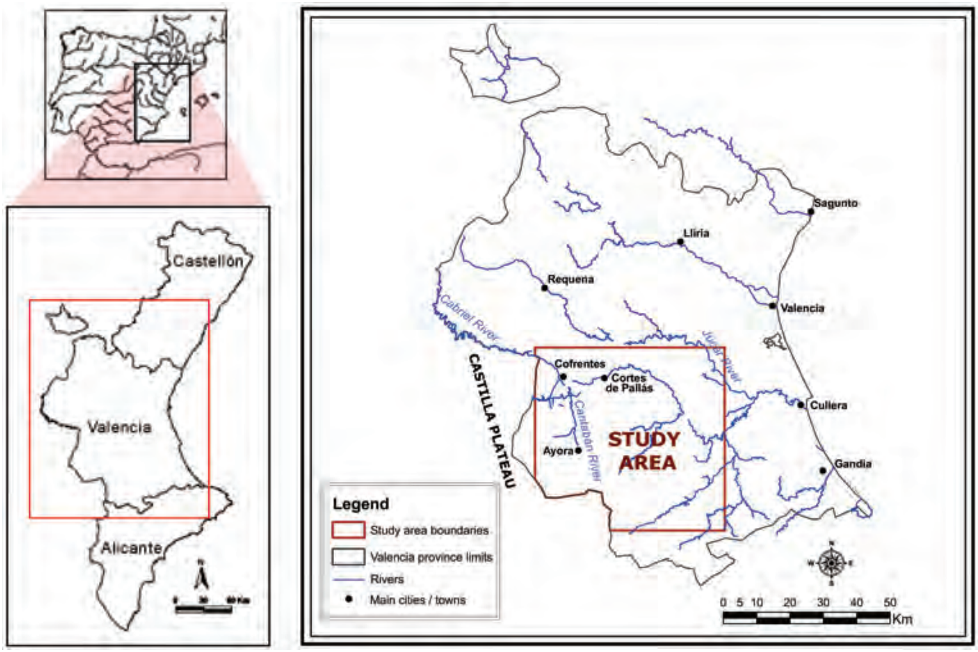
We research whether different wildland fire intensities affect the landscape in an equal mode, and whether topo-climatic variables have a consequent effect. Our hypothesis is that, in an ecosystem subjected to recurrent fires, the Enhanced Vegetation Index (EVI) measured vegetation regeneration success would depend on time (time after fire and inter-fire interval) and on biophysical conditions (topography, land cover, soil, and precipitation).

We build on these outcomes to test our hypothesis making use of EVI temporal variability in areas with different fire histories, and we relate EVI variability to emphasize vegetation dependability with topo-climatic variables. Through this analysis, we demonstrate that, at large scales, and using adequate assessment techniques, GIS and SRS are valid tools that can help resource managers and the scientific community in the Mediterranean region to plan, monitor and manage their ecosystems after fire disturbances.

2. STUDY AREA

The study area is located in the south-western part of Valencia province in the Iberian Peninsula (Figure 1), delimited by UTM coordinates SE (657, 4 301), NW (714, 4 356) of zone 30 north. It covers a total area of 287 700 ha (27% of Valencia province), where forestland prevails covering 68% of the territory, while agricultural lands covers the rest of the region contributing to the fragmentation of the natural landscape. The region is known for its complex topography with low flat valleys situated in

Figure 1. Localisation of the Iberian Peninsula (left, up), localisation of the province of Valencia (left, down), and localization of the study area within the province of Valencia (right)



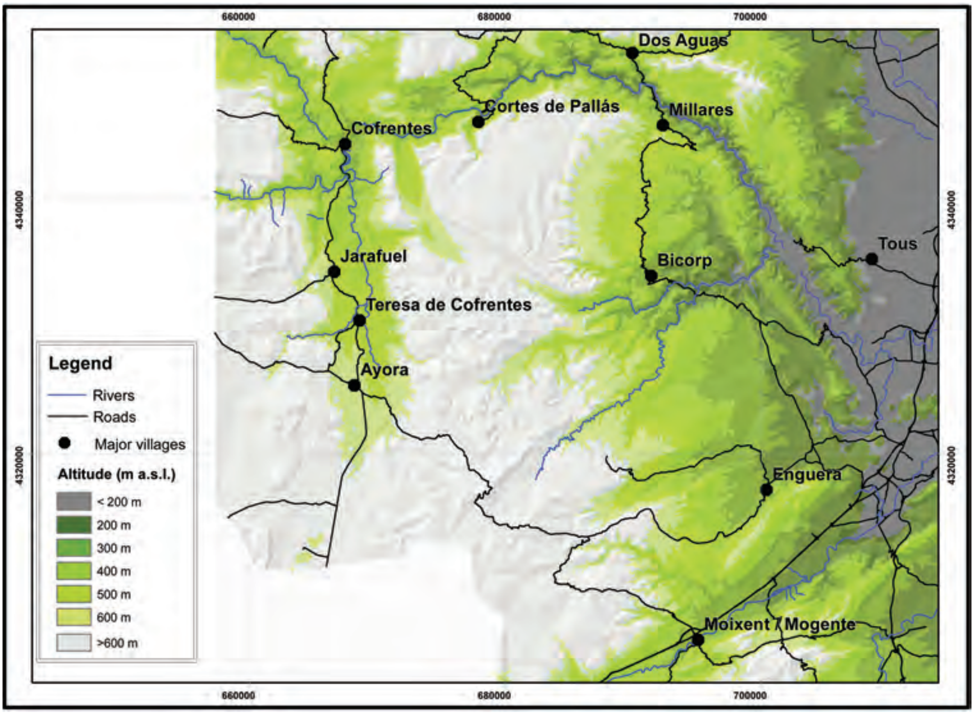
the east (around 25 m a.s.l.). The latter are formed from rivers (Turia, Júcar, and Cabriel) that bypass the region opening abrupt canyons towards the Mediterranean Sea (Figure 2). Forest is the dominant land cover in the interior and central parts where topography registers an abrupt increase in altitude from east to west. Towards the interior, a flat area is formed (the Castilla plateau) reaching around 1150 m a.s.l. in the Caroche peak (Figure 2).

The region has a typical Mediterranean climate resulting from subtropical dry anticyclones. Precipitation regime is bimodal ranging between 300 and 700 mm, rainfall is concentrated in spring and autumn (>60% of annual precipitation) with mild winters and hot and dry summers (<20%) (Pérez-Cueva, 1994). The mean annual temperature ranges between 12-16 ^{o}C in the inland forest region increasing towards the eastern side where agricultural area prevails with ranges between 16-18 ^{o}C.

Two bedrock types prevail in the study area, marls and limestone. Marls colluvium predominates around the central part forming compact, medium depth, carbonated fine soils that have low permeability and are highly sensitive to erosion. Limestone, a calcareous hard rock, produces very shallow and strongly decarbonated soils with abundant cracks and outcrops. This type of lithology, known for its low erosion and high infiltration capacity, is present in the central region producing uncultivated rocky landscapes. Small quantities of mixed soils containing conglomerates, sandstones, and clay are present in specific zones of the valleys.

The potential natural vegetation is sclerophyllous oak forest of *Quercus ilex*. As an outcome of a long history of land use changes and fire regimes, the present vegetation is a mosaic of woodland and shrublands with different development stages and species compositions. The vegetation is typical of a Mediterranean fire- prone ecosystem with a recognized ability to regenerate after fire (Trabaud, 1987). Land cover ranges from sparse shrublands to high percentages of grasses (mainly Mediterranean

Figure 2. The map of altitudes of the study area showing a complex topography with an altitudinal gradient from east to west ranging between 25 and 1149 m above sea level (A.S.L.)



gorselands with *Brachypodium* ssp.) to a dense understory of very young regenerated pine forests (Röder et al., 2008).

Over limestone, evergreen shrublands (garrigues and heathlands with varying abundance of *Quercus coccifera L.*) and pine woodlands (*Pinus halepensis*) dominate the landscape. These shrublands with different degrees of development and species composition that show no apparent pattern (Costa, 1999) cover 51% of the area.

Conifer woodlands prevail especially in abandoned terraced slopes over carbonated marl. They cover around 32% of the study area, and are mainly constituted of *Pinus halepensis* (Aleppo pine) (Baeza et al., 2007). The rest of the landscape is constituted of mixed *Pinus halepensis* and shrublands forests (17%), combined with small patches (<1%) of mixed shrublands and *Quercus ile*x (Abdul Malak, 2009).

Different studies highlight historical intense forest fire regimes in this region with a clear tendency of increasing summer temperature (Pausas, 2004) and number of observed forest fires in the last decades (Pausas & Abdel Malak, 2004). Furthermore, proven negative consequences of increasing fire recurrences (Abdel Malak & Pausas, 2006) are attributed mainly to land use changes and increasing climatic fire risk (Piñol et al., 1998). Due to its complex topography and climate, the study area has special ecological characteristics and ecosystem services that need to be protected and conserved as their exploitation constitutes one of the most important economical resources of the region (Baeza et al., 2007).

3. METHODS AND DATA

The study analyses the long term effects of repeated fires during a period of 16 years (1984

– 1999) based on a previous research that digitised and analysed the presence and extent of historical forest fires in the region (Abdel Malak & Pausas 2006). We extract the perimeters of 16 wildland fires that burned at least once during the study period from this fire database in order to assess the post-fire vegetation regeneration success in different topo-climatic conditions. We use a set of environmental, physical, and climatic parameters in our analysis to study their possible relation with vegetation regeneration.

The topographic parameters are extracted from a 25 m Digital Elevation Model (DEM) which is generated from digitized topographic maps of the Servicio Geográfico de Ejército (at the scale of 1:50.000, with contour line intervals of 20 m). The DEM is created using significant altimetric data based on the triangulation method, which creates a Triangular Irregular Network (TIN) model of the terrain. We resample the original 25 m resolution integer DEM to 30 m for compatibility and further analysis with multi-temporal satellite, from which we extract slope, aspect, and solar radiation (SR). The raster map of aspect is created in degrees (from 0- 360^{o}) and reclassified into 5 orientation intervals. SR is reclassified into different ranges forming a gradient (low to high) for every change of 2400 MJ. The altitude is reclassified into an altitudinal gradient for every 25 m increase in elevation.

We reclassify the digital 1:50 000 land cover map to categorize dominant types of land-cover based on the species present and the fraction of cover filled by each species (the % cover of each species covering a certain area). The vegetation classes are aggregated to coarser community classes, respecting vegetation type and class. The following four land cover classes are identified:

- **Shrubland (M):** this division contains areas having shrublands and *Quercus coccifera* garrigues (Q), or a mixture of shrublands and pine trees whenever the % of trees does not exceed 10%. The mixture of shrubland with *Quercus ilex L.* (M/QI) is also considered under this group.
- **Open Forest (OF):** contains natural pine forests which have a cover between 10% and 50% of the area.
- **Dense Forest (DF):** consists of pine forest areas as part of previous reforestation plans or natural forests covering more than 50% of the area.
- **Unnatural:** contains areas used for agriculture purposes (crops) as well as unproductive areas.

We limit our analysis to wildlands (i.e., including woodlands and shrublands), while the unnatural category, being human dominated is excluded from the analysis. Correlation between land cover class and vegetation regeneration is analysed on a bilateral basis in each of the studied years. Precipitation data incorporates 23 meteorological stations with complete monthly precipitation from the Instituto Nacional de Meteorología located with and around the study area and covering the study period. These data are used to calculate cumulative precipitation values for the 6 months prior to satellite image acquisition date. We use kriging interpolation method to create temporal precipitation maps for seasonal precipitation analysis.

The bedrock parameter is developed from a general reclassification of different taxonomic units of the digital geological map of Valencia (1: 50 000). Three major bedrock types (T1 to T3) are identified in the study area: Limestone (T1) is the most abundant type covering around 60% of the burned area, followed by marls (T2) (30%), and mixed soils (T3) covering less than 10% of the burned area. The datasets are introduced into a GIS, treated, and corrected, prior to their use in the analysis. The selection of these topo-climatic parameters in this research is based on a previous study (Abdul Malak, 2009) which identified, from a wider range of analysed parameters, the ones that shown significant correlation with vegetation regeneration.

Nine Landsat 5 Thematic Mapper (TM) satellite images are carried out to analyse the effect of time, fire recurrence, and topo-climatic parameters on vegetation regeneration after fire.

Table 1. Acquisition date (year, month, day) of each satellite image used in this study

Year	Month	Day
1984	6	1
1985	7	22
1986	6	23
1989	7	17
1991	4	2
1993	4	7
1994	5	28
1996	7	4
1999	6	27

Satellite images have a 30 m resolution and cover the following years: 1984, 1985, 1986, 1989, 1991, 1993, 1994, 1996, and 1999. The images' acquisition dates range between April and July, a period that corresponds to maximum plant activity ensuring their adequate comparison (Table 1).

We carry out a radiometric correction of all images in order to ensure that differences emerging from the multitemporal analyses do only result from changes in surface properties (Röder et al., 2008). This is achieved through a sensor calibration of surface reflectance removing the interfering effects of atmospheric absorption and scattering and a full modeling of the radiative transfer including a correction of topography-induced illumination variations.

We use EVI to assess vegetation regeneration success in the different parameters analysed as it proves to adequately reflect vegetation regeneration activity in the studied ecosystem (Abdul Malak, 2009). This vegetation index is optimized to enhance the vegetation signal through improved vegetation monitoring due to adjustments to its canopy background and atmospheric resistance (Huete et al., 1997).

According to the work of Huete et al. (1999), EVI is defined as:

$$EVI = G \times \frac{\left(NIR - RED\right)}{\left(NIR + C1 \times RED - C2 \times Blue + L\right)}$$

G is the gain factor and has the value of 2.5. C1 and C2 are the coefficients of aerosol resistance term which uses the blue band to correct for aerosol influences in the red band. They have the respective values of 6 and 7.5. BLUE stands for the blue reflectance. L is the canopy background adjustment that addresses non-linear, differential NIR and RED radiant transfer through the canopy. This constant is determined as 1.

4. ENVIRONMENTAL MODEL

We analyze the relation of the individual effect of the topo-climatic parameters studied (topography, climate, fire and time on shaping the landscape) on EVI- measured vegetation regeneration response after one and more fires. Afterwards, we develop a model to calculate the interactions of the previously studied parameters, in order to clarify their interactive effects on explaining EVI-measured vegetation regeneration response. The spatio-temporal model of vegetation distribution analyses EVI changes in time (years) and space (topo-climatic factors).

The mean EVI values represent values of all the pixels constituting the studied patch per year and show the extent to which complex factors interaction affect vegetation regeneration.

5. STATISTICAL ANALYSIS

Throughout the analysis, we use descriptive statistics to calculate sample sizes, mean, minimum, maximum, standard deviation, variance, sum, and standard error of the mean. This is also used for the quantification of the number of patches represented by each of the studied parameters, and their relative areas as well as for the results of the EVI obtained from the patches analysis.

The analysis of the variance (ANOVA) is used to study the effect of the qualitative or quantitative topo-climatic parameters on vegetation changes (calculated in EVI). EVI is the dependent quantitative variable, and each of the studied topo-climatic parameters is a quantitative or qualitative studied factor (explanatory variable). ANOVA is used to test the hypothesis that several means are equal. In order to compare the means, and for the discrimination of the changes in results with the different studied parameters (in the case of qualitative parameters such as bedrock, land cover, aspect, years) a pairwise post hoc test is conducted.

For the analysis of the quantitative parameters namely precipitation ranges, altitude, slope and solar radiation, correlations, multiple regressions and ANOVAs are used. ANOVA and stepwise multiple regression are utilized to validate the significant relations between EVI-measure vegetation regeneration response and the different variables. The General Linear Model (GLM) is used to study the relationship between categorical variables. This is accomplished through cell counts analysis of the cross-tabulation table formed by the cross-classification of the variables of interest. In order to test the closeness of the relationship among the studied parameters, we set up linear regression and we analyze this relation using Pearson correlation coefficient (R).For the predictive, regression equations and ANOVA, we report the coefficient of determination (R^2) to understand how changes in the predictors affect the response giving by this the proportion of the variability in the dependent variable that can be explained by the independent variable. Moreover, in order to compare the patches having different characteristics, the statistical study is done assigning a weight per relative area of the different studied patches (by simulated replication).

6. RESULTS

6.1. Burned Patches

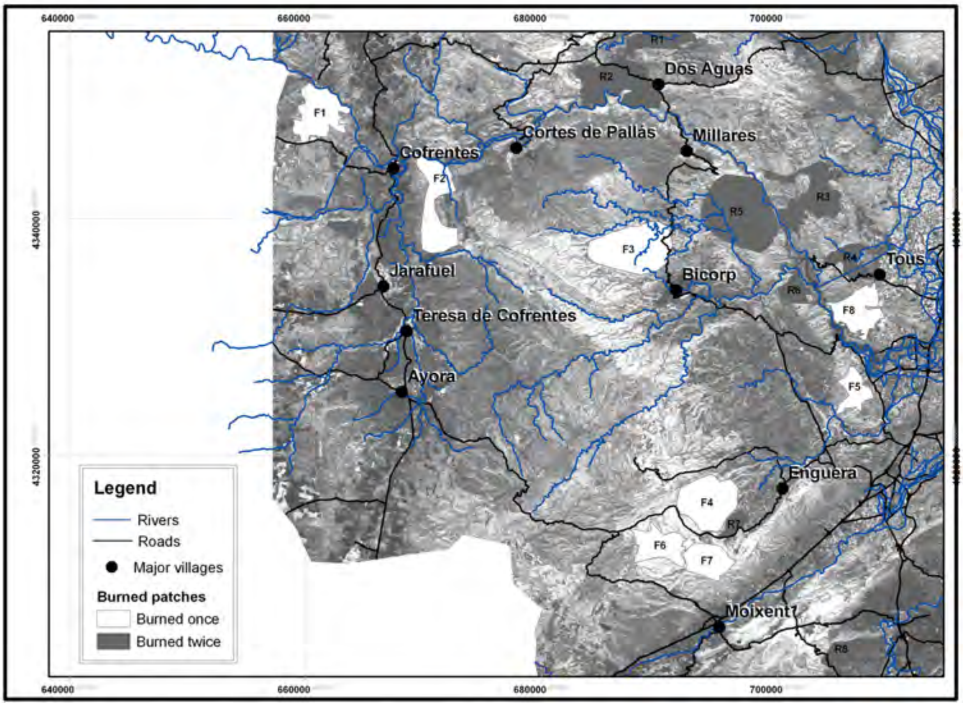
In the study area, we analyze 20 983 ha of cumulative burned forest (53% burned once, and 47% burned twice) recorded during the years 1984 – 1999 (Figure 3). The total area is composed of 16 patches ranging in size between 299 and 3 131 ha that burned at least once during this period (Table 2). The areas that burned twice (Figure 3) are separated by short time intervals (5 – 11 years).

Like the majority of fires occurring in the Mediterranean region, all the studied fires take place in the dry season between July and October. All burned areas are affected by crown fire killing the major part of the canopy. In fact, all burned areas exhibit very low EVI values after fire (between 0.07 - 0.14) (Figure 4) indicating high fire severity and leaving a homogeneous post-fire landscape in the burned sites.

In the twice burned areas, we delimit the patches burned during first and second fire events. The vegetation in these patches is analyzed as burned once from the year of first fire occurrence until next fire, and as burned twice from the year following the second fire until the end of the satellite image series.

The present vegetation regenerates after fire through resprouting or seeding regeneration strategies. During the first months following fire, resprouting species and perennial grasses recover the soil through shrub-dominated landscape quickly after fire, having a highly

Figure 3. Localisation of the once (white) and twice (dark grey) burned patches in the study area



resilient capacity. At a later stage, this vegetation slowly decreases when woody species, mainly the obligate seeders germinate from local seed banks present in soil and start to appear as isolated trees becoming finally dense bushes or forests given sufficient undisturbed period. We study the impacts of topography and irregular seasonal precipitation on the response of EVI-measured vegetation regeneration. Moreover, as forest fires occur in different areas, we study the spatial parameter as an influencing factor in post-fire EVI regeneration.

6.2. Influence of Time

We analyze the effect of time after fire on vegetation regeneration (measured in years after fire). The longest studied post-fire period is 16 years after first fire and 8 years following second fire. Years following first fire are studied until the date of second fire occurrence, 0 being the date (year) of fire occurrence (Figure 4). Directly after first fire, mean EVI values are quite low (around 0.12) resulting from the total loss of the green vegetation. A quick regeneration is registered shortly after, with a significant increasing tendency with time in the 16 studied patches (Figure 4A). Power trend line comparison shows faster regeneration during the first 8 post fire years ($y = 0.1133x^{0.38}$) than during the 16 post fire years ($y = 0.1387x^{0.19}$) suggesting a tendency to community senescence after this age. After fire recurrence, a fast vegetation recovery is recorded during the first years after fire (1 – 3 years), a conduct explained by the abundance of resprouting species including perennial grasses and herbaceous species emerging after fire. EVI-measured vegetation recovery of the 8 patches that burned twice shows a positive relation between post-fire time and vegetation dynamics ($p < 0.0001$). Compared to EVI behaviour during the first years following first fire, vegetation regeneration after second fire proves to be slower (mean EVI = 0.18) than its

Table 2. Reference of each burned patch, number of times burned during the study period, year of fire, and their respective areas in ha. In case of fire recurrence, the date of the 2nd fire and time interval separating the second from the first fire are indicated

Reference	* Burned	First Fire	Second Fire	Time Interval	Area (ha)
F1	1	1984			1461
F2	1	1985			1653
F3	1	1985			2337
F4	1	1991			1785
F5	1	1992			643
F6	1	1984			1009
F7	1	1985			956
F8	1	1994			1204
R1	2	1983	1991	8	864
R2	2	1983	1994	11	2024
R3	2	1985	1993	8	1760
R4	2	1984	1992	8	697
R5	2	1985	1994	9	3131
R6	2	1989	1994	5	487
R7	2	1985	1991	6	299
R8	2	1983	1994	11	673

regeneration after a first fire (mean EVI = 0.25) (Figure 4 A & B) suggesting a partial loss in vegetation regeneration capacity.

6.3. Influence of Topography

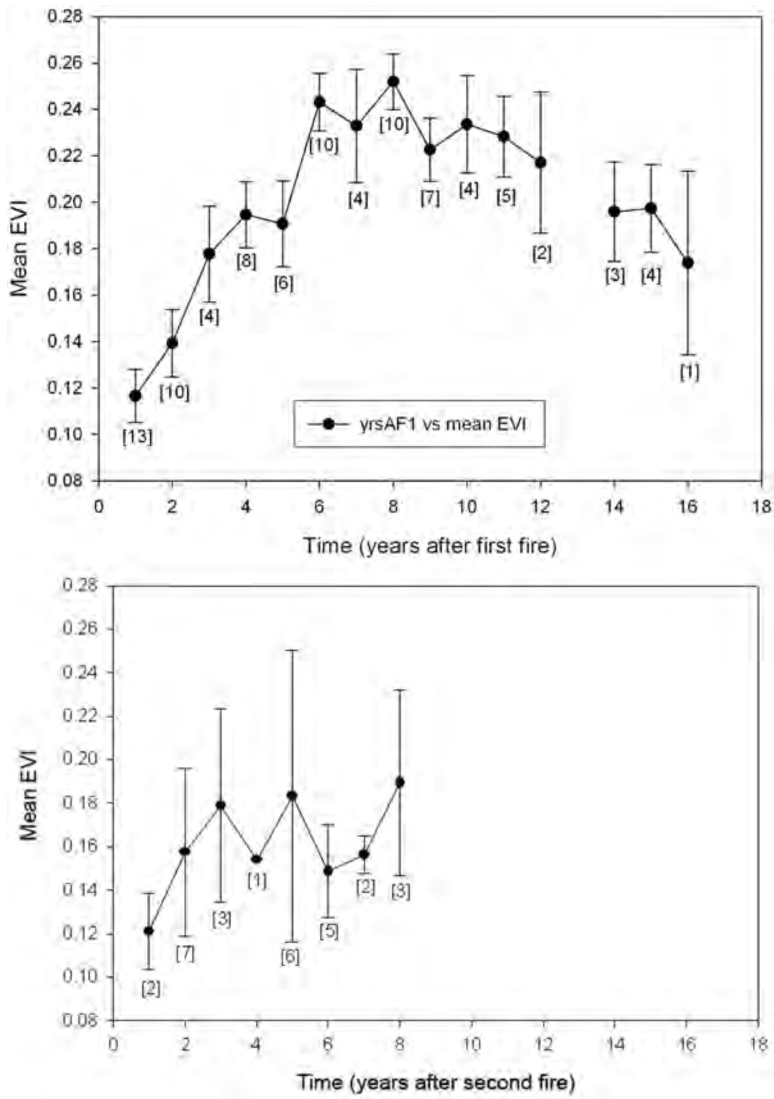
Fire shows preference of occurrence in space. Most of the areas burned once (81%) or twice (96%) accumulate at low altitudes (< 600 m a.s.l.) where more than 50% of productive forest area is present (Figure 5). Altitude shows to influence EVI-measured vegetation regeneration positively. For the 8 years following first fire, EVI- measured vegetation regeneration is positively influenced mainly by time after fire (the regression slope being $\beta = 0.884$) followed by altitude ($\beta = 0.126$) (Table 3) explaining most of the EVI variability (92%). After the second fire, time ($\beta = 0.191$) and altitude (lower $\beta = 0.152$) also show to positively affect EVI-measured vegetation changes (Table 3) but to a lesser extent, explaining 59% of its variability.

North facing orientations prove to enhance vegetation regeneration offering higher wetness and shade, where EVI regenerates faster after first fire ($p < 0.0001$) than after fire recurrence ($p < 0.05$). High SR inhibits EVI-measured vegetation regeneration, explaining 66% of its variability after first fire ($\beta = -0.311$). This negative effect exhibited by SR on vegetation is strengthened ($\beta = -0.531$) after fire recurrence, especially in high SR ranges (Figure 6), explaining 51% of its variability for the 8 years following second fire.

6.4. Influence of Land Cover and Soil

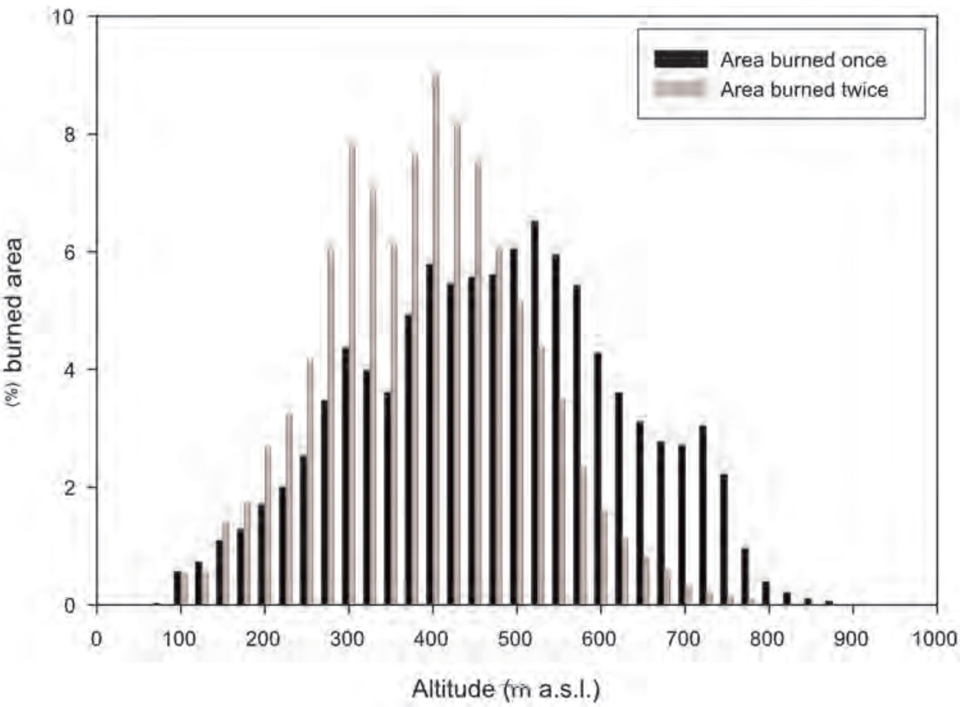
As previously mentioned, we exclude the unnatural areas from this analysis. The natural land covering areas that suffer one fire are predominantly OF (46% of areas burned once) and M (44%), whereas only 10% of the fires affect DF. Due to the short fire recurrence period (< 12

Figure 4. EVI-measured vegetation regeneration in (A) 16 forest patches following the first fire, and in (B) 8 patches following a fire recurrence. The standard deviations are shown as vertical lines and indicate the variability of EVI within the patches. The numbers under mean EVI values correspond to the number of patches considered for the calculation of the mean EVI where the number between [ ] correspond to the burned once polygons (A), and to the polygons that are burned twice (B)



years), being less than the minimum time needed for forest to regenerate to its prior state, all the areas that suffer fire recurrence are transformed into shrublands (M). Therefore, we limit our research related to land cover types to analyse EVI-measured vegetation changes of the once burned areas. Though EVI is not relevant for identifying vegetation species composition, our research reveals that EVI detects changes in vegetation communities' regeneration showing

Figure 5. Proportion of the studied area burned once (black) and burned twice areas (tan) with respect to elevation ranges



to be strongly influenced by land cover type explaining 74% of its variability.

OF, containing predominantly obligate seeders with serotinous cones (*Pinus halepensis*), shows a fast recovery during the first post-

*Table 3. Weighted ANOVA results for the effect of time since fire and altitude on EVI-measured vegetation regeneration after the first and the second fire during the 8 post-fire years. (**** P<0.0001)*

Source of Variation	**df**	**F**	**P**	
8 year period after first fire				
Time (years following first fire)	7	303.6841	<0.0001	****
Altitude	33	7.690303	<0.0001	****
Residuals	255			
Source of Variation	**df**	**F**	**P**	**Sig.**
8 year period after second fire				
Time (years following second fire)	7	12.18	<0.0001	****
Altitude	30	3.96	<0.0001	****
Residuals	193			

Figure 6. The effect of time following (a) first fire and (b) second fire as well as the negative effect of the potential solar radiation on vegetation regeneration

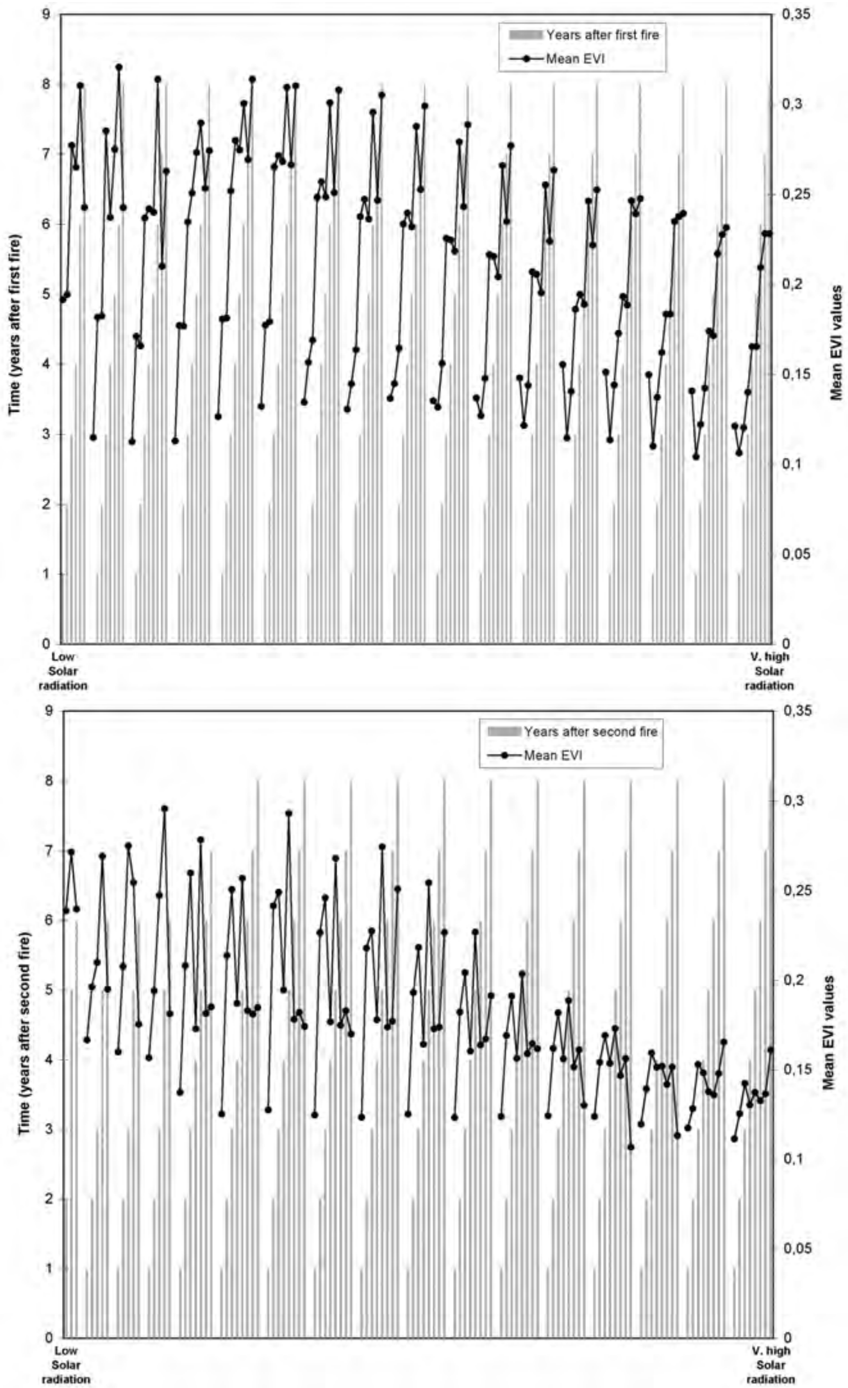


Table 4. Results of the ANOVA for the effect of time since fire, and bedrock on EVI-measured vegetation regeneration for the 8 years following the first fire and following second fire (ns: not significant, P< 0.05, ** P< 0.01, **** P<0.0001)*

Source of variance	df	F	Sig.
8 years following first fire			
Bedrock	2	3.1325	0.0462 (*)
Time (years after first fire)	7	39.1223	< 0.0001 (****)
Residuals	169		
Source of variance	**df**	**F**	**Sig.**
8 years following second fire			
Bedrock	2	0.5855	0.5600 (ns)
Time (years after first firefire)	7	3.6578	0.0024 (**)
Residuals	68		

fire years (slope for linear regression ± standard deviation is: 0.892±0.02; R^2= 0.796; p < 0.001). The regenerated plant community comes from the same species pool prior to fire occurrence, as these areas contain unburned adult trees of their own species in the canopy and thus the seed bank is large (Abdul Malak, 2009). To a lesser extent do DF (0.827±0.027; R^2= 0.684; p < 0.001) and M (0.797±0.023; R^2= 0.635; p < 0.001) regenerate during the first years following first fire. These 2 land cover types contain resprouting species (*Quercus coccifera* and scarce amounts of *Quercus ilex*) known for their resprouting ability directly after fire. In the 3 land cover types studied, EVI –measured vegetation regeneration reaches stability 6 years after first fire attaining mean EVI thresholds.

T1 is the dominant bedrock type, forming more than 60% of the landscape burned once and twice, followed by T2 (29% of the burned area). The presence of these soils is limited to flat areas of the plateau. The remaining area (11%) is mixed soils, restricted generally to steep slopes around valleys. The three bedrock types influence EVI-measured vegetation regeneration after first fire (p< 0.05). The vegetation proves to regenerate best over impermeable soils (T2), characterized by their capacity to retain water. Over recurrent fires, bedrock seems to lose its effect on EVI-measured vegetation regeneration (ns) (Table 4).

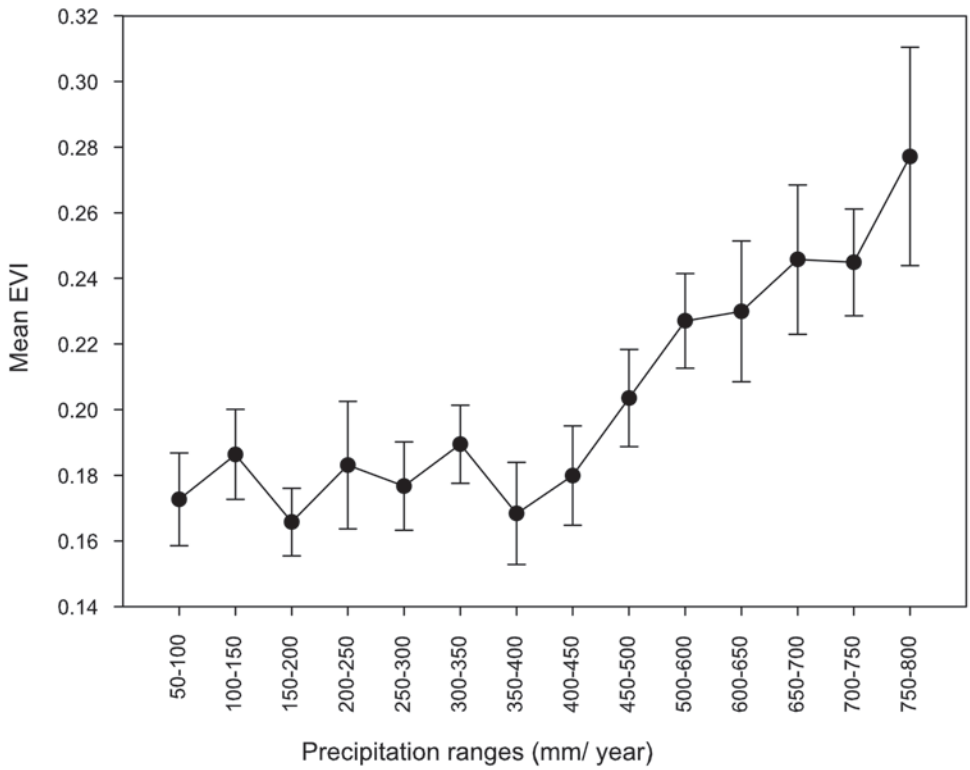
6.5. Influence of Climate

During the 8 years following first fire, precipitation ranges strongly affect (R^2 =0.92) EVI-measured vegetation regeneration at an increasingly higher rate. This positive relation is clearly revealed at precipitation ranging between 350 and 800 mm (Figure 7), whereas low precipitation ranges (<350 mm) do not affect EVI-measured vegetation variation significantly. After fire recurrence, precipitation seems to lose its effect on vegetation variability.

6.6. Driving Spatio-Temporal Trends In Post-Fire Recovery Following First And Second Fire Events

We design a spatio-temporal model to assess driving trends in shaping post-fire vegetation.

Figure 7. Mean EVI-measured vegetation regeneration in 14 (of 16) forest patches (that had at least 8 years fire interval between fire recurrences) during 8 years period following first fire versus the different precipitation ranges studied. The straight lines are the standard deviation in time of the evi values which are weighted by the area



This model analyzes the effect of ecological parameters namely fire, topo-climate, and time on EVI-measured post-fire vegetation regeneration tendencies. Correlation of pairs of explanatory ecological parameters are lower than 0.50.

The model run to all studied patches, studied parameters, number of fires (one or two) and specific study year; explains 55% of EVI's variability (Table 5). At least during the 8 years following first fire or fire recurrence, number of fire (one or two fires), time (years after fire) and water availability (precipitation and type of bedrock) prove to be key parameters influencing EVI's –measured post-fire vegetation regeneration capacity. These results provide evidence of controlling temporal and spatial trends on post-fire regeneration success proving the resilience threshold of the forests to frequent fires and drought.

7. DISCUSSION

Mediterranean communities are considered resilient to fires, being able to return rapidly to their pre-fire state (Baeza et al., 2007). However, both characteristics of fire regime (i.e. the increase in the fire frequency and severity) and harsh environmental conditions during first post-fire years (i.e. low quality soils and low or irregular water availability) play a role in decreasing survival of resprouter species and seedling establishment of seeders. Recent studies suggest that Mediterranean ecosystems may change as a result of fire intensification becoming more

Table 5. ANOVA results showing quantitative and qualitative topo-climatic variables on EVI-measured vegetation regeneration 8 years after first and second fire

Source of variance	**df**	**F**	**Sig.**	**R2**
For the 8 years after fire occurrence				**0.553**
Year	6	84.187	0.0000	
Precipitation	11	116.990	0.0000	
Bedrock	2	175.319	0.0000	
Aspect	4	18.686	0.0000	
Altitude	16	80.029	0.0000	
Solar Radiation	14	64.752	0.0000	
Fire (first vs. second)	7	513.810	0.0000	
Time (years following fire)	1	186.519	0.0000	
Fire * Time	7	41.910	0.0000	
Residuals	20881			

prone to loss in their soil characteristics and to shifts in their community types, not supporting the direct regeneration model (Eugenio et al., 2006). In such ecosystems, shifts in vegetation dynamics need to be observed after fire in order to evaluate possible ecological consequences. Our research provides evidence of influencing post-fire spatial and temporal trends on post-fire regeneration success.

At the landscape level, our results confirm that partial or total vegetation loss is the direct consequence of the increasing trend in fire regimes in the last decades. Soon after fire (1-3 years), resprouting species including perennial grasses and herbaceous species emerge covering the soil, triggered by the ‘Mineral flush’. The latter are afterward replaced by sprouting or seeding shrub-dominated communities. Our analysis proves that peak vegetation growth is registered 8 years after fire during which post-fire years are key component enhancing vegetation regeneration. After this age, vegetation tends to stabilise (Figure 4) as a result of community senescence.

Post-fire regeneration success of the canopy proves to be directly influenced by a spatial driven conduct, showing consistency across the studied years. Water presence and availability to plants insured in different circumstances like wet years, over humidity retaining soils (limestone mixed with marl), and under shade conditions proves to affect post fire regeneration (Concilio et al., 2009). The results of our model confirm these facts (Table 5), where post-fire vegetation proves to regenerate faster in east-facing slopes as a consequence of sea humidity and mild temperatures. T2 soils, due to their marl content, prove to enhance humidity acquirement and availability to vegetation in dry periods, enabling faster plant regeneration after fire.

Furthermore, the spatial distribution of fires shows to be largely influenced by topography, with a high percentage of burned areas occurring at lower altitudes (< 600 m) (Figure 5). The number of fires (one or two) limits EVI-measured vegetation regeneration decreasing significantly its regeneration pattern after a second fire. This Mediterranean ecosystems behaviour is confirmed at the plot level and remotely (Abdel Malak & Pausas, 2006; Trabaud, 1987). Lower resprouting success is registered after recurrent fires occurring in short time intervals (< 12 years); this fact is confirmed by a reduction of seeder plants including *Pinus halepensis* (Abdel Malak & Pausas, 2006; Trabaud & Galtié, 1996). This key species in the region may lose its auto-regeneration capacity being unable to reach maturity and ending up by local extinction.

Our results confirm the dependency of EVI-measured vegetation recuperation on seasonal precipitation and on soils' retaining humidity. Fires tend to conglomerate at low altitudes (<600 m) promoting rapid soil loss. These areas, subjected to warmer and drier summers prove to exhibit a likely potential to higher fire risk, while, post-fire vegetation regeneration is favoured by altitudinal gradient being positively correlated to moisture.

Potential SR proves to hinder EVI-measured vegetation regeneration, as it increases radiation hitting the ground, rising soil temperature and transpiration effects and decreasing consequently soil moisture availability. These circumstances, together with intensive fire recurrence become especially unsuitable for plants survival, registering decreasing tendencies in EVI values due to decreases in vegetation densities (Figure 6 A&B). Further consequences are soil erosion and desertification, affecting ecosystems structure, availability of nutrients, and local hydrology. This increasing fire activity and loss in vegetation quality in such areas can endanger relict stands of *Quercus ilex* present in our region, favouring the expansion of drought tolerant maquis (Vannière et al., 2010).

This spatio-temporal model is a science based tool that supports decision makers in management planning and monitoring of large forests directly after fire disturbances. Our model unveils regeneration tendencies acquired by burned areas independently from vegetation type and burned year and stresses the need of a minimum recuperation period for vegetation recovery. Explicit ecological data used demonstrates the scale adequacy of the study in identifying major parameters that affect vegetation regeneration. Some aspects remain inexplicable, highlighting the compatibility of using finer scale field data that would complete the work in test sites and reinforce the model outcomes through time.

8. CONCLUSION

This study highlights the effect of fire regimes on large Mediterranean landscapes in a non-steady state system. The model reveals changes in structure, composition, and diversity of plant communities after fire disturbances using GIS and SRS. Mediterranean natural resource managers would benefit from the efficiency of this technique in monitoring wide forest ecosystems. Further methodology testing in other Mediterranean regions will profit in developing the model further.

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