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Monitoring post-wildfire vegetation response with remotely sensed time-series data in Spain, USA and Israel

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Abstract. Due to the challenges faced by resource managers in maintaining post-fire ecosystem health, there is a need for methods to assess the ecological consequences of disturbances. This research examines an approach for assessing changes in post-fire vegetation dynamics for sites in Spain, Israel and the USA that burned in 1998, 1999 and 2002 respectively. Moderate Resolution Imaging Spectroradiometer satellite Normalized Difference Vegetation Index (NDVI) time-series data (2000–07) are used for all sites to characterise and track the seasonal and spatial changes in vegetation response. Post-fire trends and metrics for burned areas are evaluated and compared with unburned reference sites to account for the influence of local environmental conditions. Time-series data interpretation provides insights into climatic influences on the post-fire vegetation. Although only two sites show increases in post-fire vegetation, all sites show declines in heterogeneity across the site. The evaluation of land surface phenological metrics, including the start and end of the season, the base and peak NDVI, and the integrated seasonal NDVI, show promising results, indicating trends in some measures of post-fire phenology. Results indicate that this monitoring approach, based on readily available satellite-based time-series vegetation data, provides a valuable tool for assessing post-fire vegetation response.

Additional keywords: drylands, Moderate Resolution Imaging Spectroradiometer, Normalized Difference Vegetation Index, phenology, remote sensing, time series, vegetation recovery.

Introduction

Recent studies have shown that past management practices and changes in climate play a significant role in the frequency and severity of wildfires (Swetnam and Betancourt 1998; Westerling *et al.* 2006), and that climate change (e.g. CO_2 and temperature increase) is likely to impact forest fires into the future (Flannigan *et al.* 2000). In particular, wildfire disturbance is becoming more prevalent in many shrub and wooded dryland ecosystems in the south-western USA, the Mediterranean basin landscape (Swetnam and Betancourt 1998; Allen *et al.* 2002; Pausas 2004), and likely worldwide (IPCC 2007). Because of the large spatial extent and high spatial and temporal variability of dryland systems, coupled with the potential for increasing wildfire frequency and severity, robust post-fire monitoring tools are needed to inform adaptive management and advance understanding of post-fire vegetation response rates and ecosystem health. Low-cost, rapidly available, and accurate assessment of landscapes following disturbance will lead to improved predictive capabilities and more informed management decisions (Aronson and Vallejo 2006).

Vegetation cover and pattern are some of the most important parameters for assessing ecosystem and landscape functioning (Gobin *et al.* 2004; Kéfi *et al.* 2007). The growing demand for monitoring and evaluation of the impacts of disturbances such as droughts and wildfire, as well as the results of restoration and rehabilitation efforts, are motivating the development of new approaches and technologies (Tongway and Hindley 2000; Díaz-Delgado *et al.* 2002; Herrick *et al.* 2005; Kuemmerle *et al.* 2006; Lentile *et al.* 2006; Roder *et al.* 2008; van Leeuwen 2008) that can be applied at different scales and costs. The long-term evaluation of conservation and restoration success has been recognised as one of the major deficiencies in land conservation and restoration efforts (Holl and Cairns 2002).

Landsat data (30-m resolution) have been used successfully for post-fire vegetation assessments (Díaz-Delgado *et al.* 2002); however, the operational use of these data can be

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challenging because of persistent cloud cover, data continuity, acquisition and processing costs, tasking and data availability. Many studies have used the Normalized Difference Vegetation Index ($NDVI = (\rho_{NIR} - \rho_{red})/(\rho_{NIR} + \rho_{red})$, where ρ_{red} is the surface reflectance value for the red wavelength and ρ_{NIR} is the reflectance value for the near-infrared wavelength; Tucker 1979) to examine post-wildfire vegetation response processes (Malingreau *et al*. 1985; Viedma *et al*. 1997; Díaz-Delgado and Pons 2001; Malak and Pausas 2006; Hudak *et al*. 2007). Time-series data of remotely sensed spectral vegetation indices, such as NDVI, have been extensively used to evaluate trends in vegetation dynamics (Goward *et al*. 1985; Justice *et al*. 1985; Loveland *et al*. 1995), but evaluating post-wildfire vegetation response with readily available 250-m Moderate Resolution Imaging Spectroradiometer (MODIS) (Justice *et al*. 1998) time series and phenology data (van Leeuwen 2008) has been explored much less. Biweekly coarse spatial resolution (8 km) NDVI time-series data from the National Oceanic and Atmospheric Administration's (NOAA) Advanced Very High Resolution Radiometer (AVHRR) Pathfinder have been used to derive temporal anomalies for burned and unburned areas and rates of recovery for forests in Canada (Goetz *et al*. 2006), Borneo and north-eastern China (Idris *et al*. 2005), but might be too coarse for more local and regional post-fire monitoring approaches. Abrupt changes in the vegetation growth cycle or land surface phenology caused by drought and wildfire disturbance often result in anomalous vegetation growth trajectories that can be monitored with MODIS 250-m NDVI time-series data (van Leeuwen 2008).

Many studies have pointed to the need for long-term monitoring and the development of tools to evaluate ecosystem response to wildfires (US Government 2003; Mayor *et al*. 2007; Wittenberg *et al*. 2007; Rollins 2009). This research examined several novel approaches for the evaluation of post-fire vegetation response trajectories at the landscape scale. These approaches have the potential to be applied to any vegetation monitoring or restoration effort, yet also allow for comparative analyses among different sites as well as the evaluation of the success and sustainability of the management actions applied. Structural, functional and landscape quality indicators to monitor post-fire vegetation response and restoration projects can be derived from the remotely sensed data. In the present study special effort was made to ensure the generality of this research, and its applicability worldwide. To accomplish this, post-fire vegetation trends in three countries (Spain, USA and Israel) were evaluated, covering a variety of ecosystems and landscapes, and a wide range of dryland environments.

This research focussed on the potential of the following remotely sensed seasonal and spatial metrics for monitoring and evaluating post-wildfire vegetation response:

(1) Seasonal greenness or NDVI signatures, showing the amount of vegetation cover, can be used for monitoring on a biweekly basis (Goetz *et al*. 2006). These signatures can provide information on the seasonality, trend and pattern of vegetation dynamics.
(2) Trends in spatial heterogeneity at the landscape scale can be assessed through the application of spatial statistics (e.g. coefficient of variation, COV) (Barbosa *et al*. 2006) on the greenness imagery. COV represents a measure of site heterogeneity that can be calculated based on the presence and absence of vegetation cover and can serve as a means to assess fragmentation and connectivity.
(3) Phenological metrics derived from time-series satellite data can show the timing of vegetation activity in a spatial and landscape context, including: beginning, peak and end of the growing season, as well as the amount of vegetation greenness for each of these (Reed *et al*. 1994). The integration of these seasonal curves can then provide the relative amount of productivity for each growing season in the time series. Both the timing and magnitude of the vegetation greenness will provide insight into the vegetation response to environmental conditions and management treatments.

Most of these metrics are even more useful when they are combined with ground-based observations. Although ground-based observations are generally limited in their spatial extent, the remotely sensed data allow for extrapolation once the metrics are verified in the field by local experts.

Objectives

The primary goal of this research was to evaluate the effectiveness of satellite-based spatially explicit time-series data and derived vegetation phenology metrics for assessing post-fire ecosystem dynamics with respect to vegetation types, environmental controls and standard or reference conditions. To that end, the following objectives were identified:

(1) Compare NDVI data to ground data to provide a context for subsequent post-fire vegetation response analyses using the time-series satellite data.
(2) Characterise unburned reference and post-fire vegetation seasonality in response to environmental controls like temperature and precipitation events with NDVI time-series data.
(3) Evaluate how time-series NDVI data can be used to monitor post-fire vegetation cover trajectories.
(4) Assess the post-fire changes in spatial landscape heterogeneity using NDVI time-series data.
(5) Evaluate whether vegetation phenology can be used to assess post-wildfire vegetation dynamics and response.

In order to address these objectives, a research approach was designed that tested three hypotheses (H) across three dryland environments. Namely, that post-fire vegetation response:

H_1: is correlated with a positive trend or slope of the NDVI time-series data;
H_2: results in a decrease in the standard deviation of the NDVI signal over time, indicating declining spatial heterogeneity;
H_3: can be described by using trends in vegetation phenological metrics.

Our approach included the collection and pre-processing of MODIS time-series vegetation data, precipitation and temperature data, and ground-based vegetation coverestimates for each of the three study areas. The pre- and post-fire vegetation data were examined to evaluate both the temporal (H_1) and spatial (H_2) vegetation dynamics with time-series data of the burned and unburned sites, using unburned sites as a reference. Phenological metrics (phenometrics) were generated for all sites using the time-series data, after which the post-fire phenometrics were evaluated to determine their utility for describing post-fire vegetation dynamics not captured by the time series alone (H_3).

This research should result in a better understanding of the spatial and temporal patterns in greenness and phenology metrics across ecosystems. By evaluating this approach in multiple ecosystems, the most useful post-fire monitoring techniques and information can be evaluated.

Data and methods

Study areas

Two study sites were chosen in each of three study areas (Spain, USA and Israel) to investigate temporal and spatial vegetation dynamics as well as the performance of phenological metrics for detecting differences and similarities in burned and unburned (baseline or reference) sites between and within each area (Fig. 1). Study areas were selected in order to represent a variety of precipitation and temperature combinations, including the amount and timing of those combinations. Table 1 provides an overview of the site attributes including the time of the fire, burned area, temperature and precipitation variables. Note that the site in Israel partially burned a second time. Monthly precipitation and minimum and maximum temperature data were obtained for each of the three sites from weather stations near the study sites. Data for the Indian fire were obtained from a station in Prescott, Arizona, USA, ~7 km from the burned site. Precipitation data for the Guadalest site in eastern Spain were obtained from the Guadalest reservoir weather station, located in the study area. Temperature data were obtained from a station in Callosa, Alicante, Spain, ~15 km from the burned site. Mt Carmel data were from a weather station at Haifa University, located on the edge of the burned site in north-western Israel. Temperature data at the Mt Carmel site were only available since 2003.

Study areas consisted of one burned site and one unburned (reference) site (Figs 2–4). All three fire studies were intense crown fires in forests and shrublands. In each case the burned area was defined by the perimeter of the burn, and the reference site was selected based on close proximity, similar size, vegetation composition, and topographic context. Criteria used to select the specific burned sites were: (1) sufficient size to encompass at least ten 250-m MODIS pixels; and (2) a burn date within 2 years of the beginning of the MODIS record in February 2000, to allow for sufficient coverage of the post-fire land cover change trajectories and phenology. Ground-based vegetation data were collected for sites in Spain and the USA to allow for comparative analysis between ground-based vegetative cover and MODIS NDVI data.

Guadalest fire area, Alicante, Spain

The Guadalest area is located on the south-facing slopes of the Xortà mountain range, which drain to the Guadalest reservoir in the Alicante province of eastern Spain. The dominant soil type is Calcaric Cambisol (FAO 1988), developed over white marls and limestone. Steep slopes and narrow crop terraces characterise the area, located at 400–600 m elevation. The climate is dry–subhumid Mediterranean. The site represents a common mosaic landscape in Mediterranean drylands. Most of the terraces are currently abandoned and covered by pine forest or shrubland, depending on the age of abandonment. Old terraces are covered by *Pinus halepensis* (Aleppo pine) forest that naturally colonised the abandoned fields. These forest patches include a dense understorey dominated by *Rosmarinus officinalis* (Rosemary), *Erica multiflora* (Heather) and *Ulex parviflorus* (Gorse), and an herbaceous layer dominated by *Brachypodium retusum* (False Brome). The vegetation of recently abandoned terraces is dominated by tree crops, including *Ceratonia siliqua* (Carob tree) and *Olea europaea* (Olive tree), together with Aleppo pine saplings, and a dense herbaceous layer of *Brachypodium retusum* and a variety of legumes.

Post-fire vegetation cover at the Guadalest site was measured by the point intercept method (Greig-Smith 1983) in 10 50-m^2 plots, using a 0.5×0.5-m grid covering the entire plot. Total plant cover was measured 10, 20, 28, 34, 46, 57 and 70 months after the fire. These data were used to perform comparative analysis between ground-based vegetative cover and MODIS NDVI data.

Indian fire area, Prescott National Forest, Arizona, USA

The Indian fire site is located inside the Prescott National Forest, which lies in a mountainous section of central Arizona (south-western USA) between forested plateaus of the Mogollon Rim to the north and east and arid Sonoran desert to the south. Soils are derived from Paleozoic sandstones and limestones interspersed with quaternary and upper tertiary igneous intrusions. The area is dominated by a canopy of *Pinus ponderosa* (Ponderosa pine) and *Quercus emoryi* (Emory oak), with an understorey of interior chaparral species (*Quercus turbinella*, Shrub live oak; *Arctostaphylos pungens*, Pointleaf manzanita). Elevation of the two sites ranges from 1690 to 1920 m, representing a range of aspects, with slopes of up to 35 degrees. Wildfires in conjunction with high-intensity monsoon rain storms cause extensive erosion in the landscapes of the Prescott National Forest (DeBano *et al.* 1998; Neary and Ryan 2005). The Indian fire started on 15 May 2002 near Indian Creek Road in the Prescott National Forest and burned into the Prescott city limits.

Vegetation cover data were collected every spring and fall (autumn) following the Indian fire (eight collections in total). A series of three transects were measured across an untreated watershed within the burned area, one located mid-slope on each side of the main drainage and one in the center of the drainage. Each transect was 50 m long and consisted of 10 subplots, separated by 5 m along the length of a tape, for a total of 30 subplots per watershed. The data were collected as an ocular estimate of the percentage abundance of live vegetation for herbaceous, shrub and tree cover classes. These classes were summed for the purpose of this study. In addition to the cover measurements, dominant species were recorded for the burned and reference sites (J. L. Byers, pers. comm.).

Mt Carmel fire, Israel

Mount Carmel National Park includes a distinctive mountain ridge in north-western Israel and covers 250 km^2 with its highest peak at 546 m. In the past, several areas on Mt Carmel have been affected by wildfire events that burned relatively small areas (~4 km^2). The lithology is mainly composed of chalk limestone and dolomite. The slopes are steep and the streams have slopes

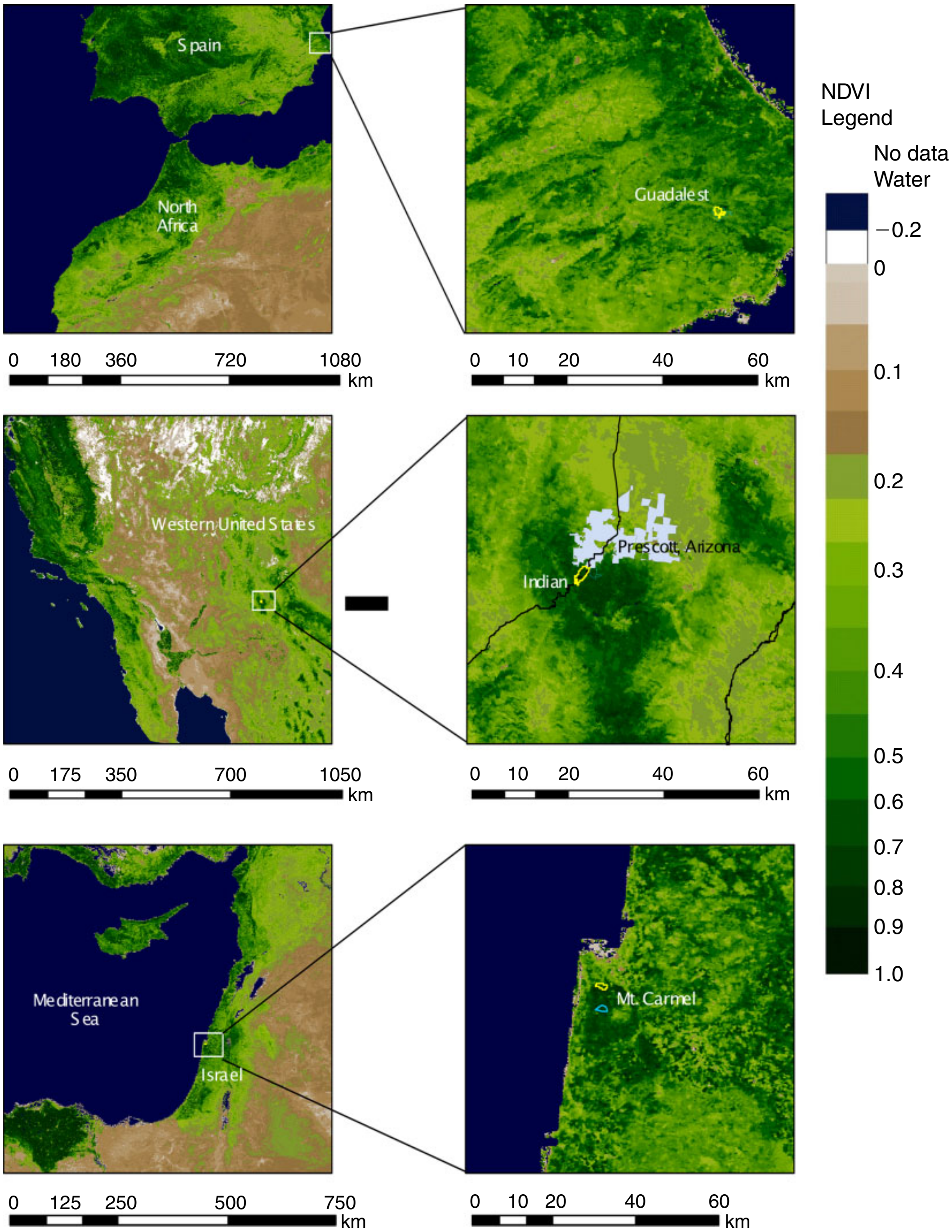

Fig. 1. Study areas for the post-wildfire vegetation response analysis in Spain (upper two images), USA (middle two images) and Israel (lower two images). The base maps are Normalized Difference Vegetation Index (NDVI) data derived from Moderate Resolution Imaging Spectroradiometer imagery. Burned sites are outlined in yellow, and reference sites are in blue.

exceeding 50% in places. The climate is Mediterranean, with dry summers and rainy winters. Fig. 4 shows representative photos of the unburned reference site and the burned site on Mt Carmel, Israel.

Naveh (1973) defined the area as a Mediterranean fire bioclimate. Vegetation on the terrarosa soils is characterised by a complex of *P. halepensis*–*Pistacia palestina* (Pistachio)–*Cistus* spp. (Rock rose) associations on south-facing slopes and *Quercus calliprinos* (Palestine Oak)–*P. palestina* associations on north-facing slopes, forming Mediterranean evergreen sclerophyll woodland. Most of the pines are not natural and were planted in the region, dating from ~80 years ago. Currently the forest that covers the area is a patchwork of natural Mediterranean vegetation and planted non-native trees of various ages.

Table 1. Summary descriptions of the three study areas, including date and area of the burned site, minimum and maximum monthly temperatures, annual precipitation and dominant season, and the dominant species found at the study sites

Sources: Guadalest data, University of Alicante; Indian data, USDA Forest Service; Mt Carmel data, University of Haifa (Inbar *et al*. 1997); temperature data, National Climate Data Center

Area characteristics	Guadalest	Indian	Mt Carmel
Burn date	Aug. 1998	May 2002	Dec. 1999; Apr. 2005
Burned area (ha)	275	550	430; 135
Temperature (°C)			
Monthly minimum	11.5	2.8	13.9
Monthly maximum	25.9	23.0	28.4
Annual	16	13	19
Annual precipitation (cm)	65.8	48.7	72.0
Precipitation season	Winter	Summer and winter	Winter

Table 2. Coefficients and associated *P*-values for the least-squares model $NDVI = \beta_0 + \beta_1\ period$, where period indicates the number of MODIS periods since burn

Regression results are shown for burned sites, reference sites, and the difference (reference − burned) between the two for burned areas in Spain, USA and Israel

Site	Burned		Reference		Difference	
	β_1	*P*-value	β_1	*P*-value	β_1	*P*-value
Guadalest	0.000202	0.00253	0.000261	0.00052	5.857E-5	0.0962
Indian	0.000791	1.275E-7	−4.218E-5	0.803	−0.000834	9.415E-14
Mt Carmel	0.00114	2.924E-5	−0.000297	0.1496	−0.00144	6.883E-15

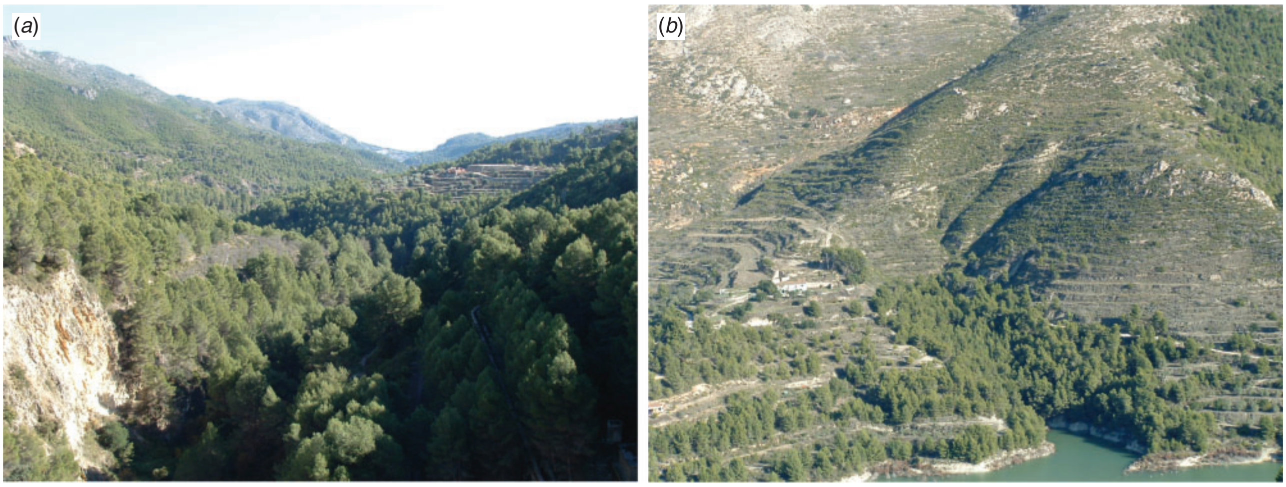

Fig. 2. Unburned mosaic of pine forest shrubland patches (*a*) and post-wildfire vegetation growth (*b*) (December 2004; 6 years after the Guadalest wildfire).

Vegetation cover in the region ranges between 50 and 70% on south-facing slopes, and between 60 and 100% on north-facing slopes.

MODIS NDVI time-series data

This study examined the use of 250-m spatial MODIS NDVI time-series data to evaluate post-fire vegetation response using some of the methods in the literature that were developed in the context of Landsat-based wildfire research. Landsat imagery (often acquired a few times a year at 30-m resolution) has been shown to be useful for identifying and mapping areas affected by wildfire, because fire causes NDVI values to decrease (Kasischke *et al*. 1993; Kasischke and French 1995; White *et al*. 1996; Fernandez *et al*. 1997; Salvador *et al*. 2000).

MODIS NDVI time-series data from March 2000 through February 2007 were obtained for northern Arizona, south-eastern Spain, and the Mt Carmel region of north-western Israel.

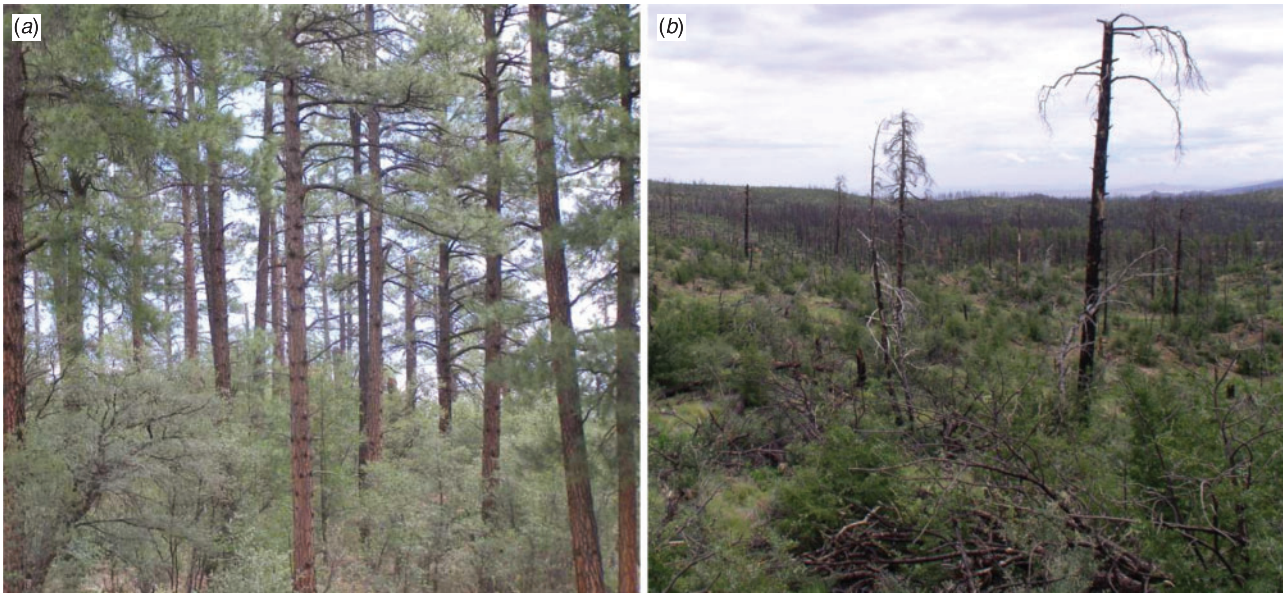

Fig. 3. Unburned mixed oak–pine forest (*a*) and post-wildfire vegetation growth (*b*) (9 September 2006; 2 years after the Indian fire).

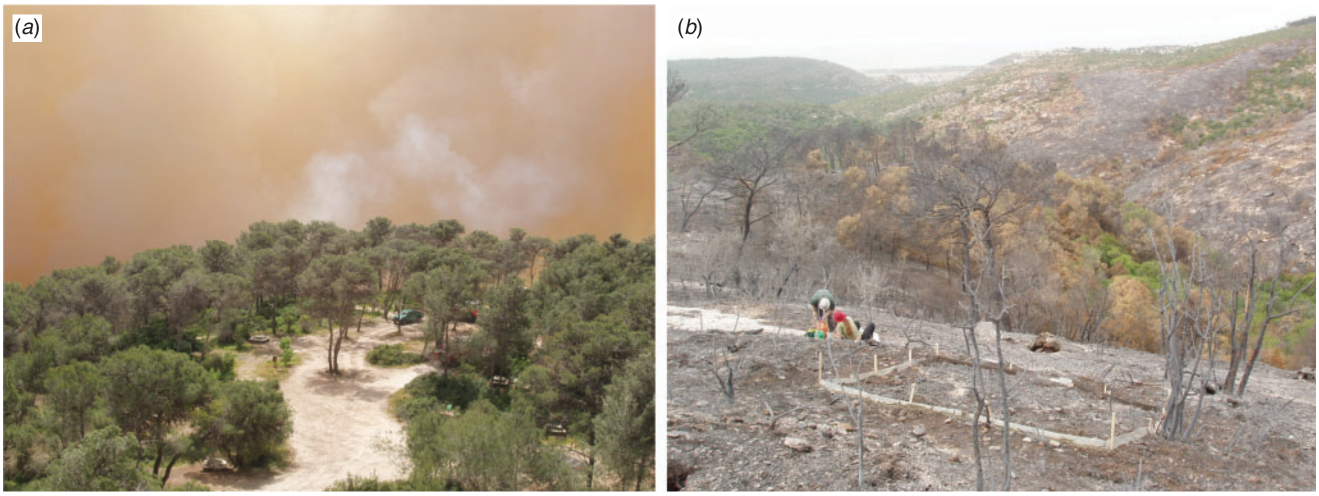

Fig. 4. Unburned mixed oak–pine forest (*a*) and the post-wildfire situation (*b*) at the Mt Carmel site (October 2006).

The primary MODIS product obtained for this study was the 16-day NDVI data at 250-m resolution, resulting in 23 16-day composite images (periods) per year. NDVI is successful as a vegetation measure in that it is sufficiently stable to permit meaningful comparisons of seasonal and interannual changes in vegetation growth and activity (van Leeuwen *et al*. 2006). Data for all three countries were downloaded from the Land Processes Distributed Active Archive Center in Sioux Falls, South Dakota, USA, and were mosaicked and reprojected into projections that matched mapping standards appropriate for each of the three countries. This resulted in a time series of 138 NDVI images for each of the three study areas.

Following this preprocessing of the data, the time series was summarised for a burned site and a reference site selected in each country – six sites in total (Fig. 1). The mean and standard deviation of all pixels within the boundaries of each site were calculated for each time step in the NDVI time series and recorded in an ASCII text file. These text files provided the basis for the evaluation of spatial and temporal trends in NDVI and the associated phenology data.

Extracting phenological metrics from NDVI time series

To date, the main approach that has been used to derive phenology for land surfaces from satellite imagery is based on curve derivatives (Reed *et al*. 1994; Jönsson and Eklundh 2002), whereby critical points are identified in the annual Vegetation Index curve that correspond to seasonal phenomena. The availability of high temporal resolution satellite data, coupled with the techniques for the analysis of seasonal and interannual vegetation dynamics, facilitate the evaluation of variability and trends

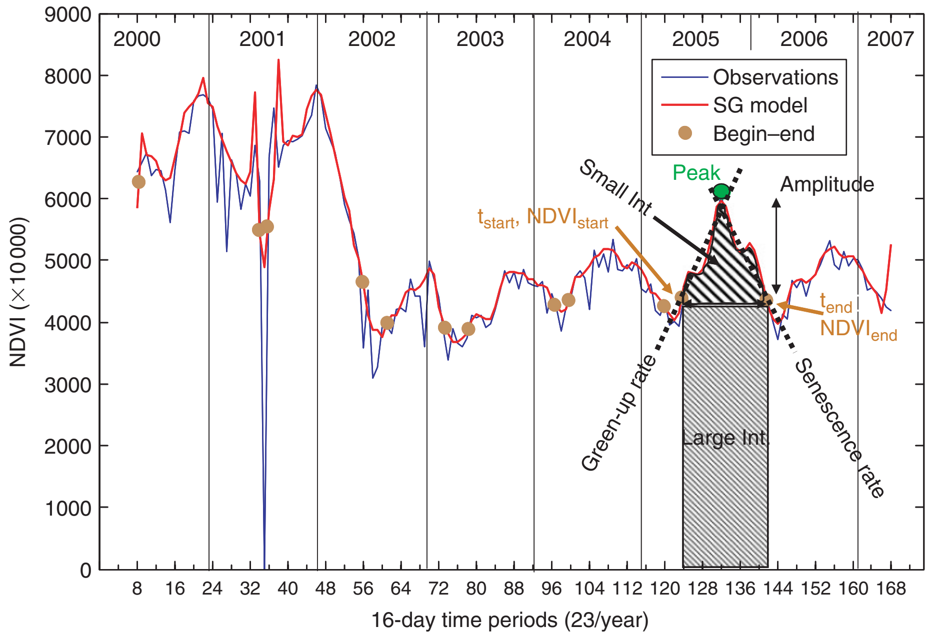

Fig. 5. Graphical example of the phenological metrics that can be derived from Normalized Difference Vegetation Index (NDVI) time series. Int, integral; SG, Savitsky–Golay.

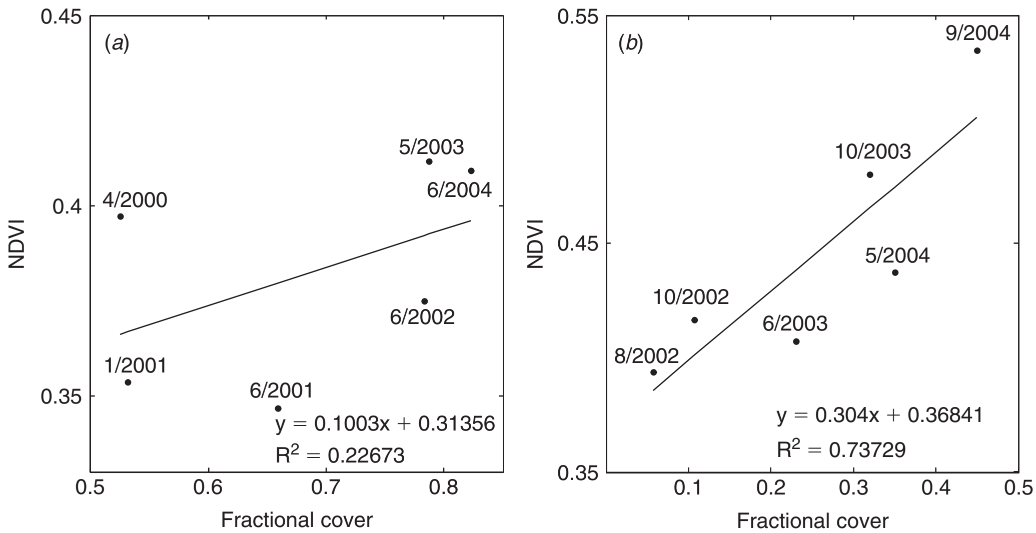

Fig. 6. Site-representative vegetation fractional cover data plotted against the mean Normalized Difference Vegetation Index (NDVI) values for the Guadalest (*a*) and Prescott (*b*) sites. Sample dates are indicated above each point.

of vegetation phenology as they relate to landscape and climate changes, disturbances and variability.

MODIS NDVI-based phenological metrics as described by Reed *et al*. (1994) and Jönsson and Eklundh (2002) were extracted yearly (based on 23 MODIS NDVI observations) to evaluate post-wildfire vegetation response for all three countries. Vegetation phenometrics of the burned sites and unburned reference sites were derived using a Savitsky–Golay filter to fit a curve to each time series of NDVI data using *Timesat* software (Jönsson and Eklundh 2002, 2004). The phenometrics were compared to determine whether they could be used to assess post-wildfire response (H_3). The seasonal phenometrics that were compared are depicted in Fig. 5, and include:

- Start of the growing season: The time (t_{start}) where $NDVI_{start}$ values start to increase is defined as the point in time for which the NDVI value has increased by 20% of the distance between the left minimum NDVI value and the maximum NDVI value.
- End of the growing season: The time (t_{end}) where $NDVI_{end}$ values level off and are at 20% of the peak NDVI value and the lowest end of the season NDVI value.

- Time of peak growing season: The time where $NDVI_{peak}$ values are at a maximum. The associated NDVI value is related to the seasonal highest amount of greenness or vegetation cover.
- Length of the growing season: The length is often indicative of the difference between the beginning and end of favourable growing conditions (e.g. precipitation and temperature limited systems in arid and semi-arid landscapes).
- Amplitude of the growing season: The amplitude is obtained as the difference between the $NDVI_{peak}$ and $NDVI_{base}$ values. $NDVI_{base}$ is the average of the $NDVI_{start}$ and $NDVI_{end}$ values. This is a measure of seasonal vegetation dynamics.
- Large integral: This metric integrates NDVI values between the zero-baseline ($NDVI = 0$) and seasonal fitted curve during the length of the growing season for each year. It is an indication of total vegetation biomass (tvb).
- Small integral: This metric integrates NDVI values during the length of the growing season that are between $NDVI_{base}$ and the fitted NDVI curve, and is an indication of new seasonal vegetation growth or productivity (svp).
- Left (l) derivative and right (r) derivative: These metrics are related to the rate of green-up and plant growth, and the rate of senescence respectively.

MODIS time-series data were summarised for each of the burned and reference sites using *Timesat* to generate 11 phenometrics for each year, although *Timesat* did not generate metrics for the last year of the record due to insufficient data to complete the seasonal determinations (Fig. 5). This resulted in a total of 6 years of metrics for each of the sites.

Data analysis approach

Comparison of field-based vegetation cover to MODIS NDVI

Vegetation cover data were collected to evaluate the ability of radiometric data in the form of NDVI to represent ground-based biophysical data such as percentage vegetation cover for two of the three ecosystems under investigation. Field data collected at the Spain and USA field sites were compared with MODIS NDVI values for dates corresponding to the field collection dates. The degree of correlation between field and satellite data was assessed by calculating the coefficient of determination (R2) between the two datasets.

Visual interpretation of time-series data

As a first step in understanding the value of MODIS time-series data for monitoring post-fire response, the data for the three sites were evaluated by visual interpretation in conjunction with precipitation and temperature data for each of the study areas. Such visual interpretation can reveal nuanced responses in temporal vegetation patterns to climatic events such as drought or unusual periods of precipitation, as demonstrated by Kasischke *et al*. (1993), who used Landsat-based NDVI data for visual analysis of pre- and post-fire NDVI response. These observations can further an understanding of changes in wildfire risk or post-wildfire vegetation response. The causes of some differences in seasonal patterns between regions can also be seen by interpreting the MODIS NDVI time-series data, as differences in the timing of precipitation and temperature between regions result in unique seasonal vegetation patterns.

Evaluating post-fire NDVI trends

In order to test the hypothesis that post-fire vegetation response is associated with a positive trend of the MODIS NDVI time-series data (H_1), trends in time-series NDVI data were evaluated for each of the three countries, similar to Viedma *et al.* (1997) and Díaz-Delgado *et al*. (2002). Viedma *et al*. (1997) calculated Landsat-based recovery rates based on the relationship between the NDVI and time. Díaz-Delgado *et al*. (2002) showed that the ratio between the mean NDVI of burned and unburned areas can be used to evaluate post-fire recovery in Catalonia, Spain, based on several Landsat scenes.

The post-fire MODIS NDVI time-series data for the burned areas were evaluated by testing for a significant post-fire response slope. To do this the post-burn NDVI data were fitted using the simple linear regression model: $NDVI = \beta_0 + \beta_1\, period$, where *period* indicates the number of MODIS periods since burn. The relationship was tested for significance at $\alpha = 0.05$. This same test was repeated for the reference sites and after subtracting the time series of the burned sites from that of the reference sites. Coefficients (β_1) for each relationship were tested for significance in order to evaluate the use of a reference site to account for variations in vegetation communities to local environmental conditions.

Spatial heterogeneity analysis

Post-wildfire landscapes are typically characterised by a high degree of spatial variability in the early stages of post-fire vegetation dynamics due to variations in burn severity and the distribution of biotic and abiotic factors and legacies (Turner *et al*. 1999). Over time, however, dominant vegetation types may exert an increasing degree of control over the function of the ecosystem (Holling and Gunderson 2002), resulting in an overall decline in spatial heterogeneity within the burn perimeter. The COV (standard deviation divided by the mean) has been used with satellite-based time-series NDVI data to indicate changes in spatial heterogeneity over time (Barbosa *et al*. 2006). We used the COV trajectories to provide a measure of the change in relative heterogeneity of each of the selected sites.

To compare and evaluate the trends in spatial heterogeneity for the three countries (H_2), the COV for both the burned and unburned sites for each MODIS composite period between 2000 and 2007 were calculated. The COV was computed by taking the ratio of the standard deviation to the mean (Gotelli and Ellison 2004) of the NDVI values of all pixels within each site's perimeter. The corresponding differences between the COV_{burned} and $COV_{reference}$ sites were then computed for each period. As with the mean NDVI data, we used the post-fire simple linear regression model $COV = \beta_0 + \beta_1\, period$, where *period* indicates the number of MODIS periods since burn, to quantify the rate of change in spatial heterogeneity.

Phenological comparison and analysis approach

The evaluation of phenometrics for use in post-fire vegetation assessment involved the analysis of three primary relationships, defined by the metrics derived for each study site. First, phenometrics were compared between the reference sites in the three regions. This was done in order to evaluate the ability of the derived phenometrics to discern differences between the three regions, unrelated to wildfire disturbance events. Second, the metrics derived for each area for the burned and unburned sites were compared in order to identify those metrics that best described trends in post-wildfire vegetation dynamics. Third, the phenometrics for the burned sites across the three regions were evaluated by pooling the post-burn metrics of all three, after taking into account the behaviour of the reference sites for each region. This was done in order to determine the value of using a reference site, as well as the degree to which post-fire response across regions is similar or different.

To compare reference sites between the three regions, each metric was averaged across the 7 years to create a representative description of the phenology for each of the three study areas. For each metric, differences in the means of the metric across regions were tested using a pairwise comparison of the means ($\alpha = 0.05$), after accounting for multiple comparisons using a Tukey–Kramer adjustment (Ramsey and Schafer 1997).

Changes in post-fire phenometrics were evaluated by testing the rate of change in each metric as a function of year since burn. This was done first for each study area separately, and then by pooling the data from the three areas. In each case the relationships were evaluated using the burned area alone, as well as using the reference area to account for differences in local dynamics and variable climatic conditions. In the case of the timing-based metrics (start, end, and peak timing, as well as length of the growing season), and the two metrics related to the rate of green-up and senescence (left and right derivatives), the burned area metrics were subtracted from those of the reference area, as interpreting differences for these metrics is more intuitive by considering a simple difference. For the magnitude-, svp- and tvb-related metrics (base, peak, amplitude, and the small and large integrals), burned metrics were divided by reference metrics to account for the potential for non-linearity in the increases in differences between burned and reference metrics given increases in overall productivity of both burned and reference sites. These metrics are also easily interpreted in terms of a percentage of the reference values. All results from the Israel fire were presented for the period of record before the occurrence of the 2005 fire. The second recurrent fire in 2005 partially overlapped with the 1999 fire and was therefore treated separately in the analysis.

Results and discussion

Comparison of field-based vegetation cover to MODIS NDVI values

Fig. 6 shows an example of how the NDVI values increased with higher fractional vegetation cover at the Guadalest and Prescott fire sites. Although the relationships of NDVI and a biophysical parameter like the fractional vegetation cover are often site specific and vary with the optical properties of soil and vegetation, and with phenological stages, NDVI usually increases with increases in cover. Variability in the position of the sensor and sun can also diminish the strength of the relationship between the NDVI and fractional vegetation cover (van Leeuwen *et al*. 1994). Fig. 6*a* shows a fairly strong linear relationship for the Prescott site and indicates that the maximum fractional cover (peaking in September–October) and corresponding NDVI were higher each consecutive year after the fire. The relationship between the NDVI and fractional cover for the Guadalest site is less strong because the MODIS monitoring period started 2 years after the fire, with vegetation already covering more than 50% of the surface, changing slowly during the following years, and with seasonal and interannual variation masking the slight response trend of NDVI values. Starting in 2002, plant cover stabilises around 80%, whereas NDVI values continues to vary until the end of the monitoring period, probably reflecting the response of the vegetation to climatic variation (Figs 6, 7). In addition, total vegetation cover was measured, including both senescent and live vegetation. Senescent vegetation has a low NDVI response and can obscure green vegetation, which by itself results in high NDVI values (van Leeuwen and Huete 1996). These results suggest that MODIS NDVI values are highly sensitive to changes in vegetation cover for low to moderate cover values.

Visual interpretation of weather and MODIS NDVI time-series data

Time-series NDVI, precipitation and temperature data show the post-wildfire seasonal vegetation dynamics between 2 and 8 years after the wildfire as well as their response to climate variables at the Guadalest study area; time-series NDVI data for the reference site with similar original vegetation are depicted as well (Fig. 7). The amounts and seasonality of vegetation, as indicated by the NDVI values, are similar for both areas and are still fairly close in NDVI levels, with the area that burned having slightly but consistently lower levels of NDVI than the reference area over the course of the study period. This consistent difference can be associated with the shift in the vegetation community that occurred after the wildfire, with pre-fire pine forest patches moving to gorse shrubland (*U. parviflorus*) communities after the fire. Moreover, during regular field visits after the fire, it was observed that the vegetation in the shrubland patches recovered rapidly, whereas vegetation in the pine forest areas recovered more slowly, showing very poor regeneration of pines and moving to a more gorse-dominated shrubland.

The timing of the lowest NDVI values are observed to occur in the summer months, whereas the highest NDVI values are observed during the fall and spring, which are the periods combining wet soils and warm temperatures. The dynamic range of the NDVI is lower for the Guadalest region than for either the Prescott (Fig. 8) or Mt Carmel (Fig. 9) regions.

Time-series NDVI, precipitation and temperature data are shown for the Prescott region in Fig. 8 to demonstrate the pre- and post-wildfire vegetation dynamics. The Indian fire started on 15 May 2002. Fig. 8 shows the NDVI time series for the region of the fire just before the burn, shortly after the burn, and for some time after the event. The NDVI trajectories are similar for the two sites before the time of the fire, including a consistent decline in actively photosynthesising vegetation over the nearly 5-month period immediately before the fire (Fig. 8). The drought trend at the Indian fire area most likely indicates that the large amount of vegetation present in January had dried up just before the fire.

The drought in the spring of 2002 is pronounced in the precipitation data shown (Fig. 8). For most years more spring rainfall was measured compared with 2002. Prior to the fire the areas have similar NDVI levels, with the area eventually consumed

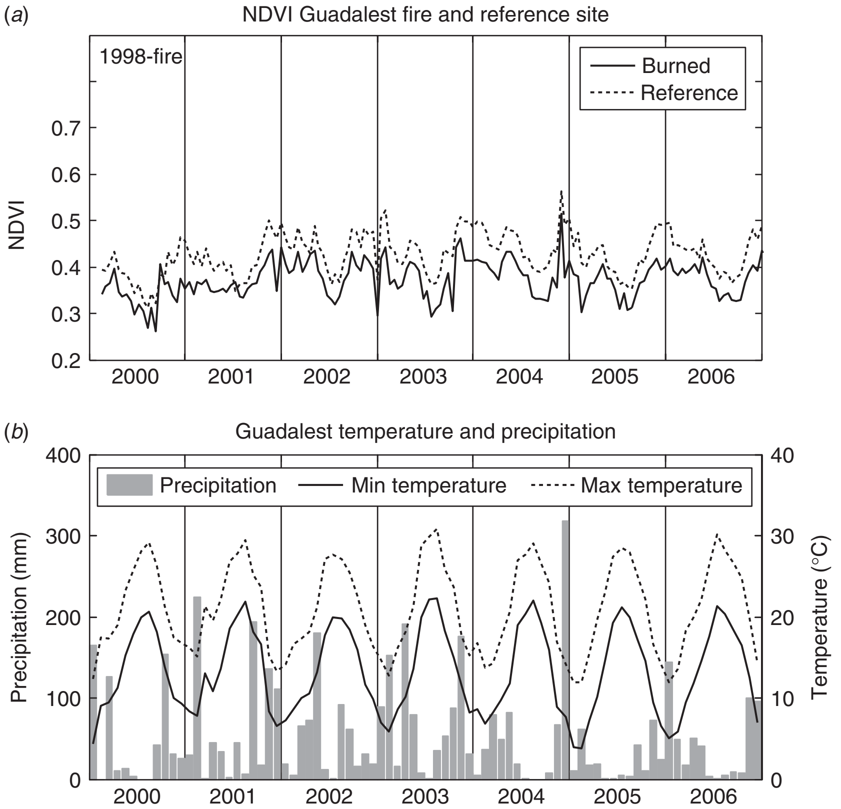

Fig. 7. Moderate Resolution Imaging Spectroradiometer 250-m Normalized Difference Vegetation Index (NDVI) time-series data for the burned (1998 fire) and reference sites from nearby Guadalest (*a*) and precipitation, minimum and maximum temperature data (bottom) from nearby Guadalest, Spain (*b*).

in the wildfire having slightly higher NDVI values than the reference area just before the fire. It is important to note that the Indian fire started on 15 May, yet the compositing process of MODIS NDVI data selects for the maximum value across the 16-day NDVI composite period. Therefore, the fire was detected in the composite image of the following period. One year after the peak in the previous year's growth the difference between the peaks in vegetation of the burned and unburned areas can be clearly seen. Four years following the fire the difference remains clear, although the NDVI time-series curves indicate that the gap between the two areas has diminished. After the 2002 drought, the unburned reference site continued to have lower NDVI values than before the 2002 drought (Fig. 8). Investigation on the ground has shown, however, that although the burned region is being restored by planting ponderosa pine seedlings (in 2006), it is not returning quickly to its prior state of pine forest, but is rather moving to an interior chaparral vegetation type. Field visits in 2005 and 2006 showed that post-fire vegetation was dominated by resprouting shrub species, including *Q. turbinella* (Shrub live oak) and *Juniperus deppeana* (Alligator juniper), with a herbaceous component of grasses and forbs (Fig. 3).

The timing of the lowest minimum and maximum temperatures coincide with the lowest NDVI values. During these times, the overstorey oak and pine growth stops and herbaceous vegetation senesces or is covered by snow. NDVI values for pixels covered with snow or senescent vegetation tend to be ~0.15 or lower.

The Mt Carmel fire started in 1999. Time-series NDVI, precipitation and temperature data are shown for the Mt Carmel region in Fig. 9 along with the pre- and post-wildfire vegetation dynamics and their response to weather variables. The time-series NDVI data for the reference site with similar original vegetation that was not burned is shown as well. The amounts and seasonality of vegetation, as indicated by the NDVI values, have similar patterns for both areas. The differences between the yearly minimum and maximum NDVI values are larger for the burned site than the reference site. Nine years following the fire, the difference is still clear, although the NDVI time-series curves indicate that the gap between the two areas is diminishing, especially in 2003. The timing of the lowest precipitation and maximum temperatures coincide with the lowest NDVI values. The timing of the minimum NDVI values usually occurs later in the year at the burned site than at the unburned reference site (Fig. 9).

Evaluating post-fire NDVI trends

Regression of the post-fire NDVI for burned sites, reference sites, and the difference between the two (Table 2) shows that analysis of the burned site alone can lead to confusing and misleading results. When looking at the burned sites alone,

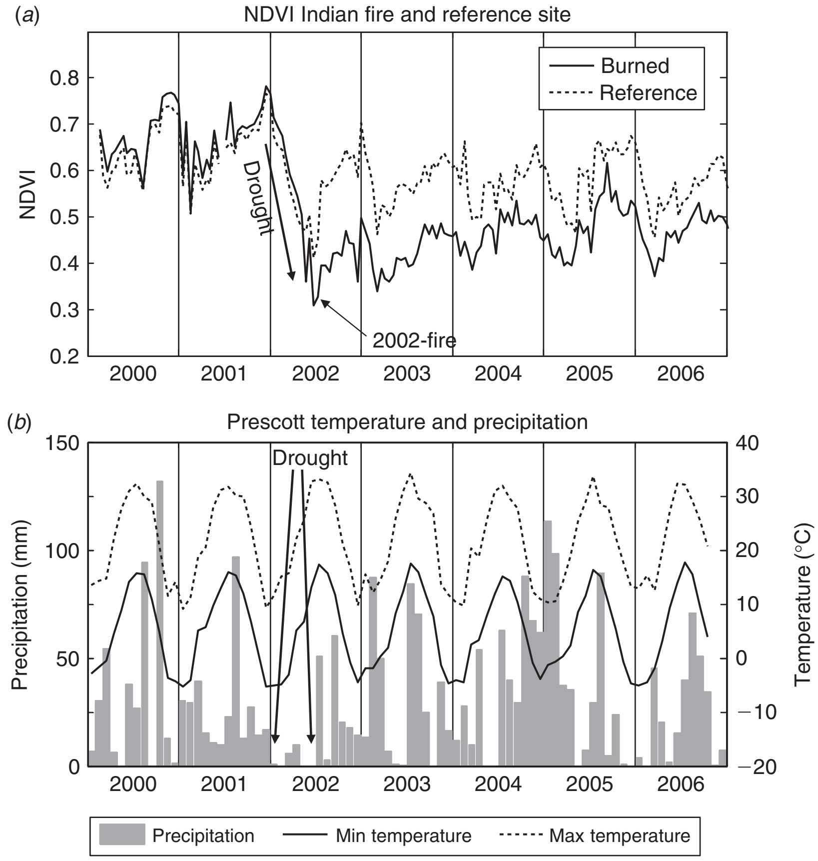

Fig. 8. Moderate Resolution Imaging Spectroradiometer 250-m Normalized Difference Vegetation Index time-series data for the Indian fire site and the unburned reference site on the Prescott National Forest near Prescott, AZ, USA (*a*) and weather data from nearby Prescott, AZ, USA (*b*). The 2002 drought and fire events are indicated with arrows.

results show significantly positive slopes for all three burned sites. However, the slope for the post-fire period at the reference site for Guadalest is very similar to that of the burned site. This can be seen visually in the time-series data (Fig. 10) and quantitatively in the values of the model coefficients (Table 2). The difference between the burned and reference sites does not indicate a significant post-fire slope for the Guadalest fire. This may suggest that there is a trend in the vegetation that is independent of the effects of the fire, and that the NDVI index is unable to detect a difference between that trend and any post-fire effects that may exist. This trend could also be associated with climate variation. During the first 3 years after the fire (until 2001), an extremely dry period occurred in the area, resulting in stressful conditions for vegetation performance, followed by a relatively wet period and the associated response of vegetation in both burned and unburned sites. Data for the Mt Carmel fire does not show a significant trend when the burned site alone is observed. This is most likely due to the large seasonal amplitude at that site, which adds to the variability of the site and makes significance more difficult to establish (Fig. 10). By subtracting the reference site, these seasonal differences are largely eliminated, and a highly significant trend is seen for the difference between the burned and reference sites.

Results from the regression models for the difference between burned and reference sites in all three countries are illustrated in Fig. 10. According to the trajectories for the difference between reference and burned sites (Fig. 10, Table 2), the Guadalest site and, to a lesser extent, the Indian site are still very far from closing the gap between their pre- and post-fire NDVI time-series curves. In both cases, a change in the type of vegetation community is observed after the fire.

Mediterranean plant communities generally include many species that have the ability to resprout from stumps or have the capacity to successfully regenerate from seed after fires. The most common post-fire pattern is the autosuccession of the plant community, so that burned sites reach a state similar to the pre-existing (unburned) one (Trabaud and Lepart 1980). However, it has also been reported that vegetation structure and biomass may become dominated by a few shrub species, particularly when fire disturbance returns within short time intervals (Díaz-Delgado *et al.* 2002). This type of shift in plant communities has also been observed after large wildfires in some pine forests in south-western USA (Narog 2008) where previously shade-suppressed oak shrubs vigorously resprout after fire whereas pine regeneration is prevented because of the distance to seed sources.

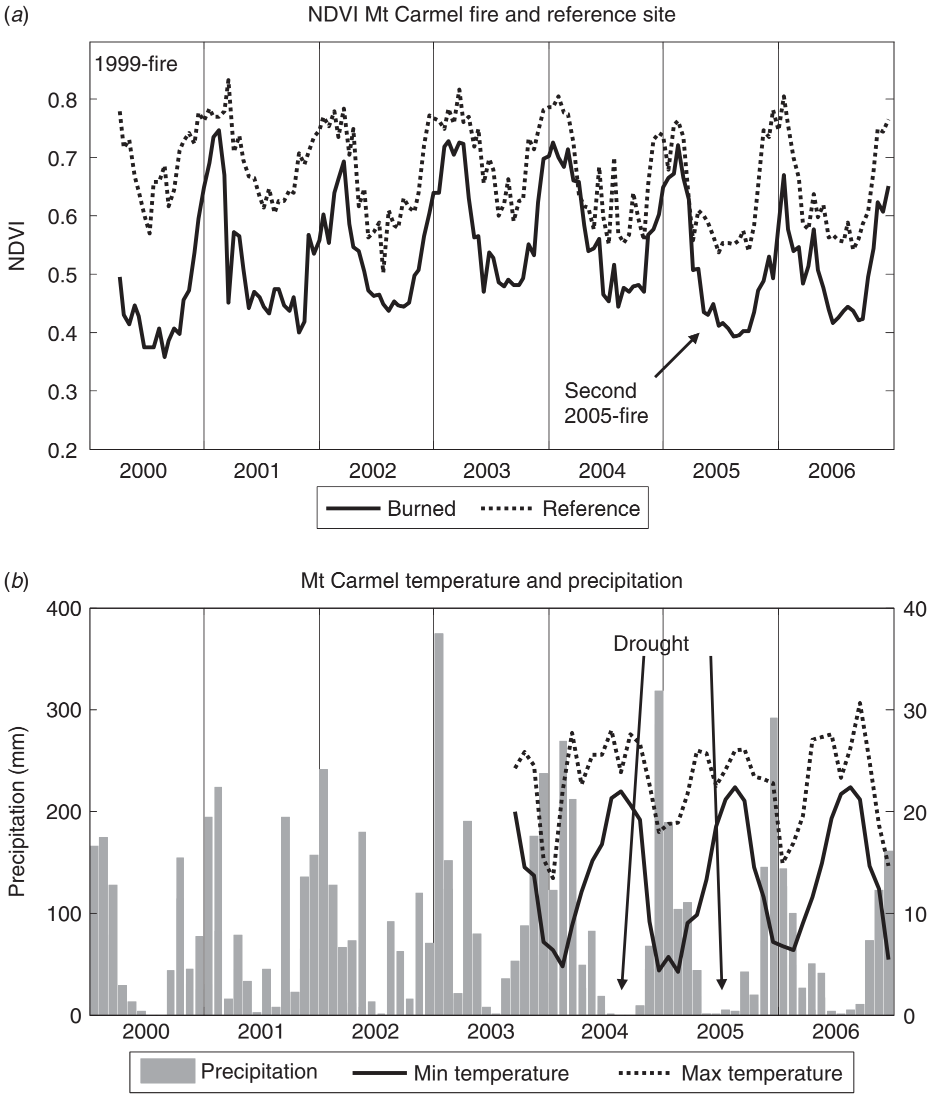

Fig. 9. Moderate Resolution Imaging Spectroradiometer 250-m Normalized Difference Vegetation Index time-series data for burned and reference sites on Mt Carmel, Israel (*a*). Note that a second fire occurred on part of the site that was burned in 1999. Precipitation data are shown for years 2000–06, and minimum and maximum temperatures were plotted from the second half of 2003 through 2006 (*b*). Weather data were collected from nearby Mt Carmel, Israel. The Mt Carmel fire site first burned in 1999 and burned again in 2005. Drought and fire events are indicated with arrows.

Post-fire spatial heterogeneity trends

Analysis of the post-fire COV show significant post-fire trends in declining spatial heterogeneity using the burned area alone, without comparison to a reference site (Table 3). Results for the reference sites show some very small, yet significant, trends in heterogeneity for the Guadalest site, but not for the Mt Carmel or Indian sites (Table 3). The results for the difference between COV of the burned and reference sites all show a decrease in heterogeneity over time (Table 3). These results suggest that the reference sites can be considered stable with respect to spatial heterogeneity in response to environmental conditions over time. Plots of the COV over time for the three burned sites are shown in Fig. 11. Our results show a consistent decreasing trend in the landscape-scale vegetation heterogeneity with time after fire. This may indicate that the differences in NDVI between patch, interpatch and intrapatch areas are highest after the fire and slowly diminish with time after the fire. Therefore, at the landscape level, fire alters the patch structure of the burned area. Similarly, Turner *et al*. (1999) found that variations in burn severity and the redistribution of resources across the burned area resulted in a heterogeneous post-fire landscape.

Rates of regeneration of the pre-existing spatial relationships among vegetation patches vary across the presented post-fire ecosystems. Ricotta *et al*. (1998) found that the post-wildfire recovery of the spatial distribution of vegetation patches can be quite rapid, especially for ecosystems with resilient vegetation

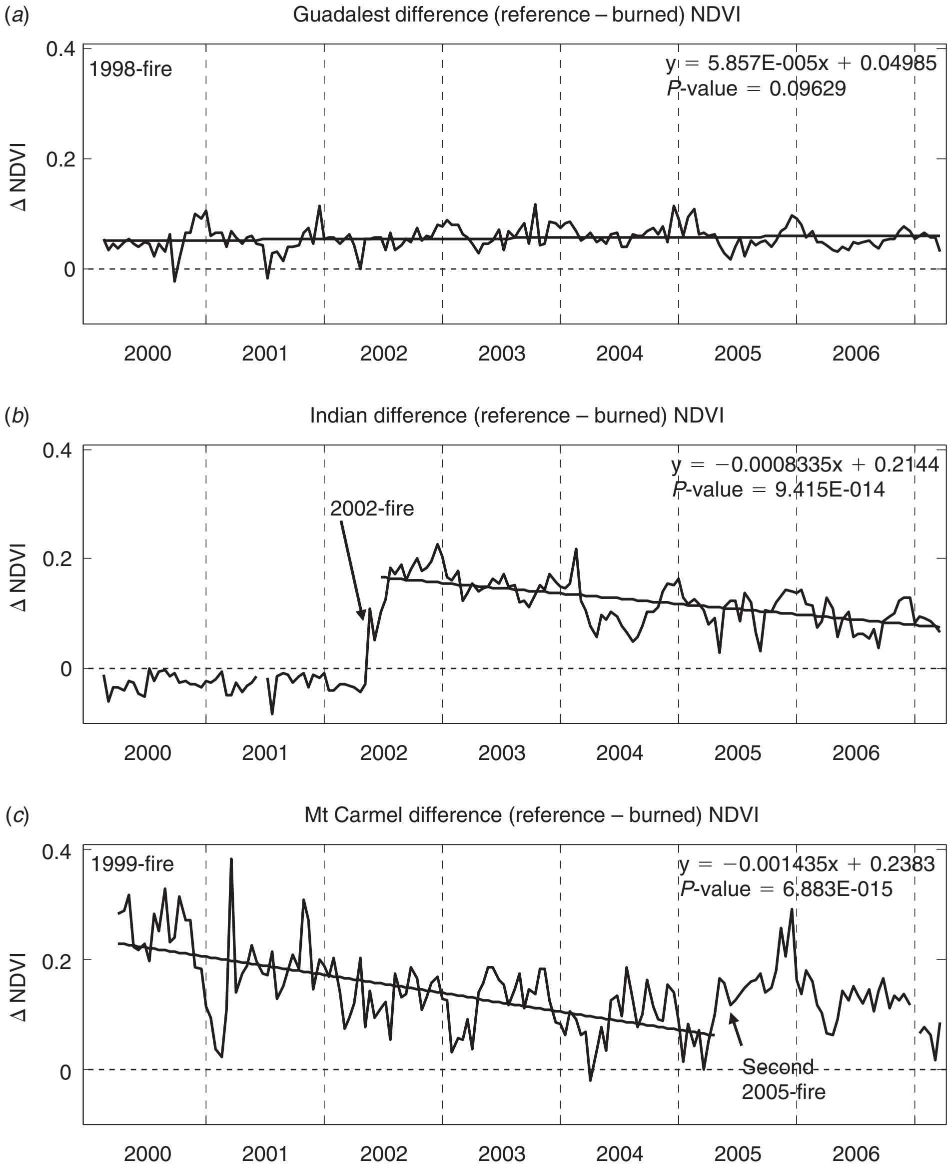

Fig. 10. Time-series Normalized Difference Vegetation Index difference, showing the trends of post-fire burned sites subtracted from reference sites. Post-fire linear trends are significant ($\alpha = 0.05$) for the Indian (*b*) and Mt Carmel (*c*) sites, but not for the Guadalest site (*a*). Note that the Mt Carmel data from the time after the second fire occurred were excluded from the trend analysis.

such as those found in Mediterranean ecosystems. At the Guadalest site it is found that the wildfire favours the spread of gorse shrubland, particularly in those land-use patches most severely affected by the fire due to the rapid colonization of *U. parviflorus* on disturbed soils (Baeza *et al.* 2003). Thus, in south-eastern Spain, the wildfire facilitated a shift from pine forest patches into gorse shrubland communities, and rejuvenating already existing gorse shrublands, possibly resulting in weaker trends in post-fire landscape heterogeneity compared with the Mt Carmel and Indian sites.

Evaluation of land surface phenological metrics

Species composition often changes after recurring and severe wildfire events. For example, the regeneration patterns of three Mediterranean pine forests changed significantly after a large wildfire in north-eastern Spain, resulting in a transition to oak-dominated communities and shrublands (Retana *et al.* 2002). In mixed *P. ponderosa* (Ponderosa pine), *Quercus gambelii* and *Q. emoryi* (Gambel and Emory oak) forests, a major crown fire results in many charred snags (Passovoy and Fule 2006) after which native organisms and plants often vigorously return or

Table 3. Coefficients and associated *P*-values for the least-squares model $COV = \beta_0 + \beta_1$ *period*, where period indicates the number of MODIS periods since burn

Regression results are shown for burned sites, reference sites, and the difference (reference − burned) between the two for burned areas in Spain, USA and Israel

Site	Burned		Reference		Difference	
	β_1	*P*-value	β_1	*P*-value	β_1	*P*-value
Guadalest	−0.000408	5.028E-05	−0.000188	0.0010	0.000586	2.88E-11
Indian	−0.001221	1.163E-10	0.000177	0.0954	0.001307	1.61E-14
Mt Carmel	−0.000903	2.727E-11	−0.000167	0.0690	0.000735	4.821E-08

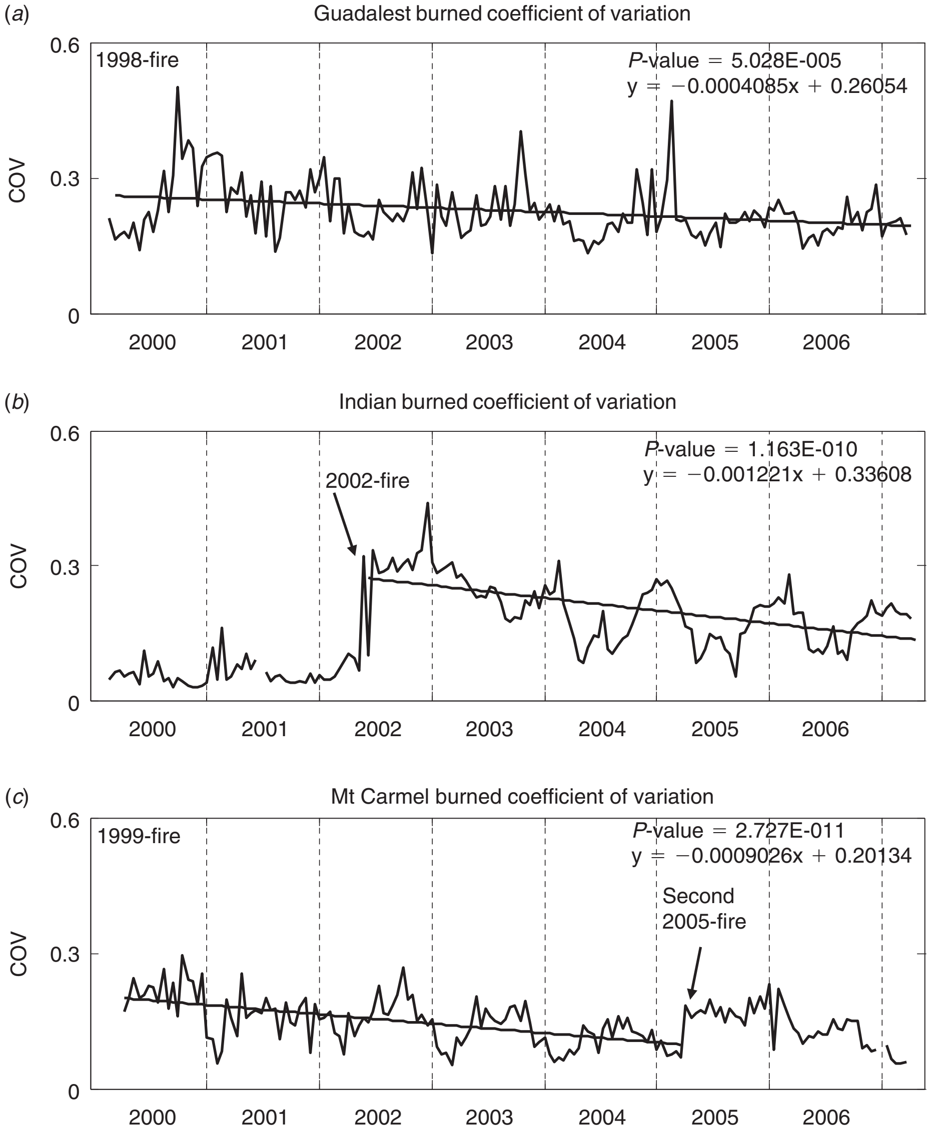

Fig. 11. Time-series coefficient of variation (COV) showing the trends of post-fire burned sites. Post-fire linear trends are significant ($\alpha = 0.05$) for the Guadalest (*a*), Indian (*b*) and Mt Carmel (*c*) sites, indicating a decrease in spatial heterogeneity since the burn at all three sites. Note that the Mt Carmel data from the time after the second fire occurred were excluded from the trend analysis.

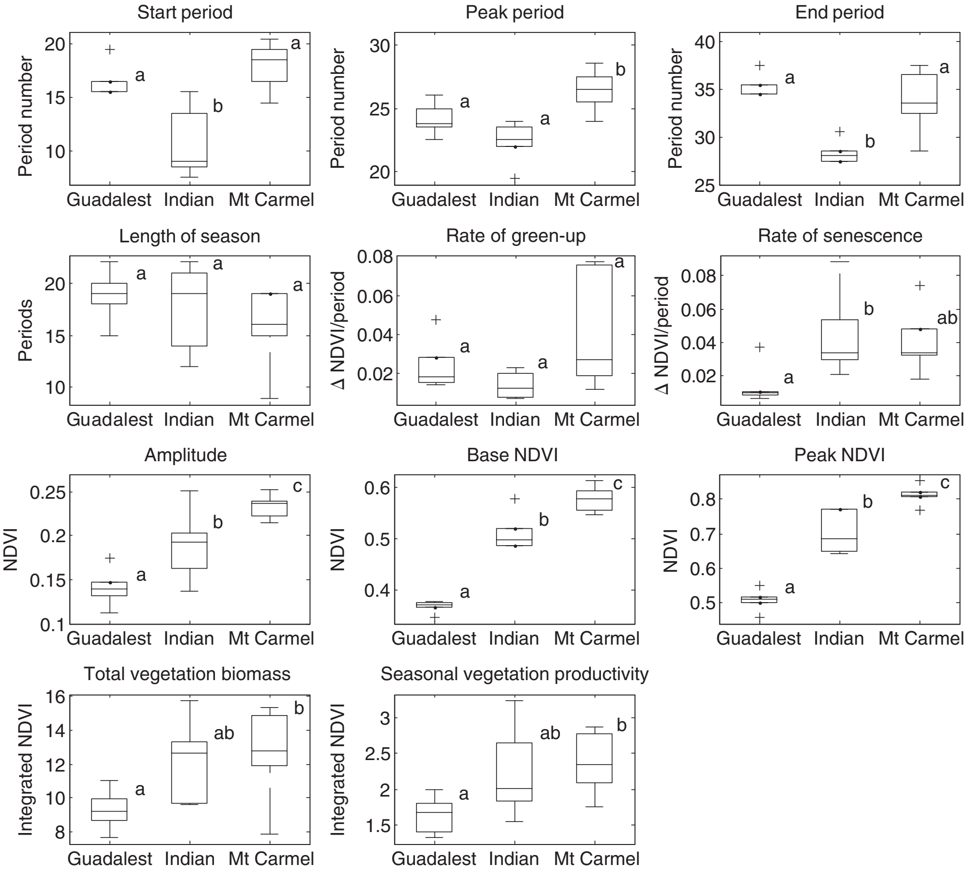

Fig. 12. Boxplots showing the median and standard deviations (lower and upper quartiles) for each of the eleven metrics tested between reference sites (Guadalest, Indian and Mt Carmel). Any data observation that lies more than 1.5 × interquartile range (IQR) lower than the first quartile or 1.5 × IQR higher than the third quartile was considered an outlier, indicated with a '+' sign. The smallest value and largest value that are not outliers were marked by a horizontal line connecting by a vertical line to the box. Boxplots labeled with the same letters (a, b, c, or a combination thereof) for each metric indicate that the median for that metric does not differ significantly between sites.

resprout at the site and initiate recovery. On the other hand, in many of these charred areas, invasive species are able to establish themselves (Crawford *et al*. 2001), often crowding out native species. Because the phenology of a vegetation community reflects the species that are most dominant, we expect that the changes in species distribution and communities caused by wildfire disturbances (Bataineh *et al*. 2006) will be observable with a time series of vegetation greenness.

Evaluations of phenological metrics across the three regions show both similarities and differences between the three reference sites representing the regions (Fig. 12). In particular, the timing of phenological events, including the start and end time for the growing seasons, are significantly different ($\alpha = 0.05$) between the two Mediterranean regions (Guadalest and Mt Carmel) and the USA site (Indian fire), whereas these metrics are very similar for the two Mediterranean sites. It is interesting to note, however, that the duration of the growing season does not differ significantly between the three regions. These differences in phenology between the three regions are most likely due to differences in the amount and timing of precipitation and temperature patterns at each of these sites. Rainfall in the Mediterranean regions comes primarily in the winter but temperatures remain high enough for year-round growth, thus resulting in starting periods in the late fall. In contrast, precipitation in central Arizona, USA occurs in both the summer and winter months, with a dry period in the early spring, accounting for the differences in start of growing season from the Mediterranean sites. Site-specific differences in the rates of green-up (left derivative) and rates of senescence (right derivative) are largely inconclusive.

Phenological metrics related to NDVI magnitude, in particular the amplitude, base, peak, and proxies for total vegetation biomass (large integral; $NDVI_{tvb}$) and seasonal vegetation productivity (small intergral; $NDVI_{svp}$) also show significant differences among the three areas. Guadalest generally shows the lowest NDVI values, although it receives higher average annual precipitation than the Indian fire site (Table 1). Based on $NDVI_{tvb}$ and $NDVI_{svp}$ data, the productivity at the Guadalest site was lower than the productivity at the Mt Carmel site, and the productivity of the Indian site falls mostly in between these two. It may

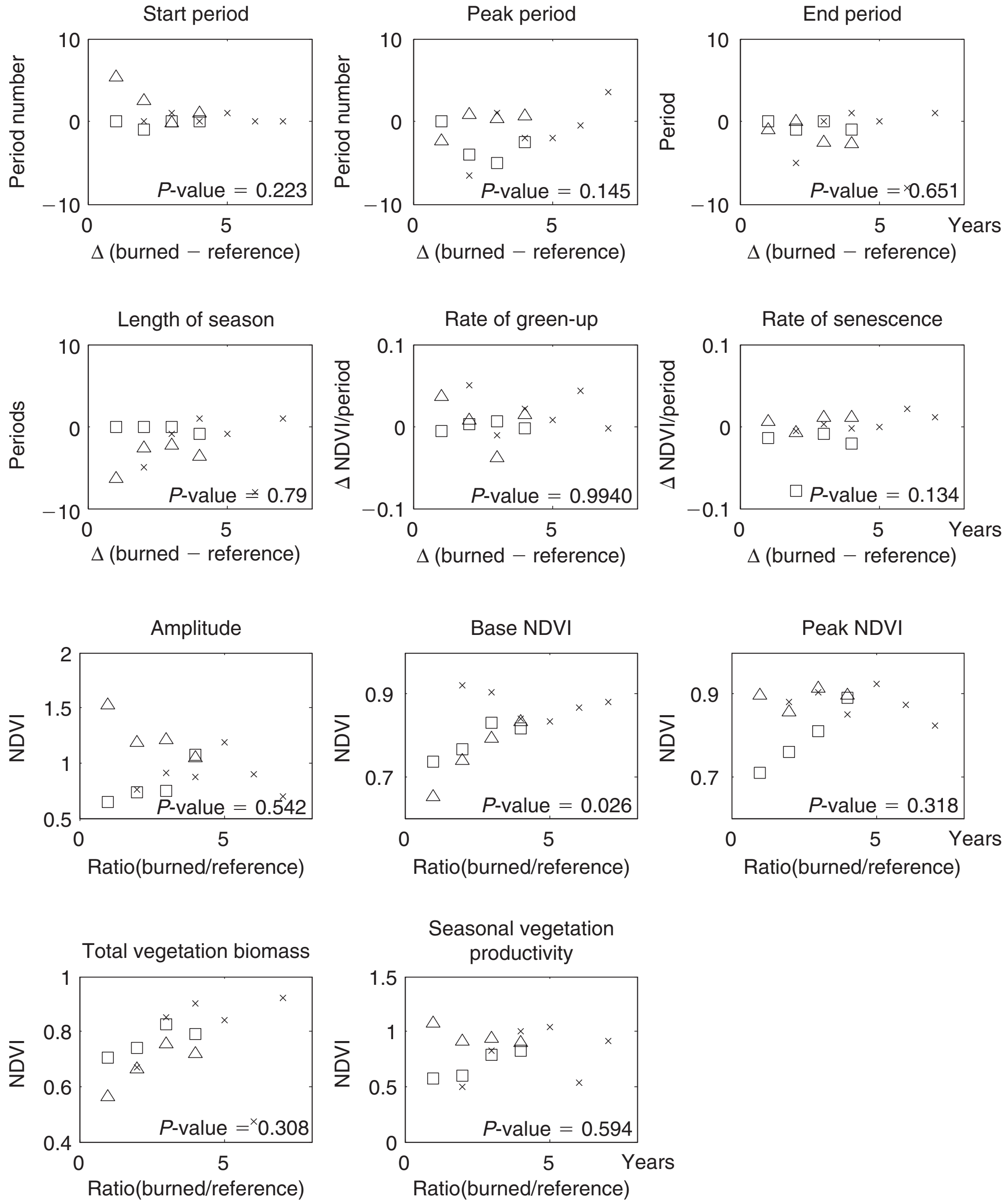

Fig. 13. Pooled differences between burned and reference area phenometrics, where timing-based metrics (start, peak and end periods, length of season) and rates of green-up and senescence were calculated as differences of the burned minus the reference metrics and the base Normalized Difference Vegetation Index (NDVI), peak NDVI, amplitude, biomass and productivity were calculated by dividing the burned by the reference metrics. From these metrics, only the base NDVI showed a significant (P-value = 0.026) post-fire trend. The x-axis represents the number of years after the fire event. ×, Guadalest; □, Indian; ○, Mt Carmel.

be that higher temperatures at the predominately south-facing slopes at the Guadalest site result in more annual evapotranspiration and thus less productivity compared with the Indian fire site. Differences in soil properties could also play a role in site-specific productivity.

The phenometrics that are associated with the burned sites were normalised with the phenometrics of the reference site for the Guadalest, Indian and Mt Carmel study areas in order to assess trends and variability in the phenometrics as they change over time after the fire event (Fig. 13). Visual interpretation suggests some trends and site-specific variability. However, statistically significant post-wildfire trends are not observed for the majority of the site-specific phenometrics. Exceptions to this include an annual increase of the peak NDVI at the Indian fire site when compared with the reference site ($P = 0.0022$), and increases in total vegetation biomass (large integral;

$P = 0.0376$) and base NDVI values ($P = 0.0289$) for the Mt Carmel fire.

Similarly, no significant trends are evident for most of the phenometrics after pooling the three areas. The one exception to this is the base NDVI values, which increase with time since burn when pooled. Visual observation of the data that contribute to this relationship between $NDVI_{svp}$ and number of years after burn (Fig. 13) reveals that the Indian and Mt Carmel fire data contributed to a linear relationship throughout the post-burn period, but the Guadalest fire do not show the same linearly increasing relationship.

Overall, although the phenometrics seem to differentiate well between vegetation communities in diverse sites (Fig. 12), the data used here do not demonstrate that there is agreement in the trends for all of the sites or that the phenometrics reveal the more subtle shifts that might indicate changes in post-wildfire community phenology.

Conclusions

The rapid rate at which ecosystems are being degraded by both natural disturbances and human activities is the impetus for ecological restoration and conservation efforts worldwide. This is especially true in drylands, where the synergy of anthropogenic and climatic drivers has lead to desertification processes and presents a serious threat to natural resource management for ecological and societal sustainability (IPCC 2007). Monitoring the effect of disturbances such as wildfires is especially important in drylands, as these sensitive ecosystems are being degraded and desertified at a fast rate worldwide. However, large-scale monitoring of post-fire vegetation response is very costly and time consuming. There is a need for a common methodology for baseline evaluations of post-wildfire effects at the stand and landscape scales. Field and multiscale satellite observations are both valuable and often synergistic. Care should be taken that these data sources are used judiciously to fit the specific characteristics of any particular management effort and allow for comparative analyses between different actions or inactions. Although post-wildfire vegetation response is affected by fire severity, vegetation community characteristics and environmental controls (DeBano *et al*. 1998; Turner *et al*. 1999), future research will need to address how the presented remotely sensed seasonal and spatial metrics for monitoring and evaluating post-wildfire vegetation are impacted by differences in fire severity.

This research demonstrates how moderate-resolution satellite-based spatially explicit time-series data and derived vegetation phenology metrics can be used for assessing post-wildfire ecosystem dynamics with respect to mixed shrub and forest vegetation types. The inclusion of a standard or reference site to normalise for environmental controls that affect both burned and unburned sites is shown to be critical for quantifying trajectories in spatial and temporal vegetation response metrics of all three sites recovering after recent wildfires. MODIS NDVI time-series data (250-m resolution) are successfully used to characterise unburned reference and post-fire vegetation seasonality in response to environmental controls like temperature and precipitation. Time-series NDVI data are shown to be an effective tool for monitoring both unburned and post-fire vegetation cover trajectories. In addressing the first hypothesis, it is demonstrated that post-fire vegetation response trends had a positive trend or slope of the NDVI time-series data for the Mt Carmel and Indian sites. The Guadalest site shows a consistent difference between the burned and unburned reference sites, but without any trend or slope in the NDVI time-series data after the fire.

Analysis of the post-fire changes in spatio-temporal heterogeneity using NDVI time-series data confirms the second hypothesis, showing a decrease in the standard deviation of the NDVI signal over time for all three sites, indicating declining spatial heterogeneity with time. The evaluation of remotely sensed vegetation phenology for assessing post-wildfire vegetation dynamics and response shows some promising results. Trends in vegetation phenological metrics that described post-fire vegetation response trajectories are observed for the Indian and Mt Carmel sites but are less clear for the Guadalest site. The variables related to the timing of the growing season show few trends among all three sites with respect to changes in the timing of vegetation response after wildfires.

These results also show that analysis of both the original time-series data, as well as summaries of such data in the form of phenometrics, can provide useful insights into differences between vegetation communities. For both the time series and the phenometrics, more mesic sites seem to lend themselves more readily to post-disturbance analysis compared with xeric sites, possibly due to an increased signal amplitude relative to the noise inherent in MODIS NDVI time-series data.

In making inferences regarding the general applicability of phenology in evaluating post-disturbance vegetation dynamics, we noticed two potential challenges. First, the MODIS NDVI product used here is a 16-day composite. It is quite possible that subtle shifts in the timing of phenological events due to disturbances are not detectable at this temporal resolution. Further work should be done with datasets of finer time scales before concluding that changes in the timing of biological events associated with the disturbance of plant communities are not discernable using phenometrics.

Second, this analysis involved a narrow time window of at most 8 years since burn, which was limited by the period of record for the MODIS sensor. Thus sample sizes were small relative to the amount of interannual variability one might anticipate for natural systems. This resulted in challenges in establishing significance for post-fire phenological trends. Further attention to these and other burned sites may reveal trends over a longer term than is seen here. This then constitutes a general constraint to the use of annual phenology metrics derived from remote sensing datasets of limited duration in the determination of trends in areas of recent disturbance.

Post-fire management units need tools to both monitor the effect of wildfires on ecosystem health and evaluate the effect of post-fire vegetation management. There are several structural, functional and landscape quality indicators required for making informed decisions. This research provides a few promising monitoring protocols that can potentially augment the indicators and tools available to post-fire management. Management activities could include, among others, replanting, salvage-logging, grass-seeding, application of mulch, pellets or straw. The actual applications of these protocols for the evaluation of management practices needs further evaluation and must take into account spatial scales and frequency of required observation (e.g. Landsat and MODIS). The proposed monitoring tools and presented results suggest that these protocols can provide information about seasonal and interannual trends in the post-wildfire vegetation response and allow for comparative analysis among countries. These research results suggest that the presented monitoring tools for post-wildfire vegetation response assessment based on 250-m MODIS NDVI time-series data could contribute to and be an integrated part of post-wildfire monitoring protocols. The presented tools are cost effective, and could provide near-real-time assessments of post-fire vegetation response, addressing a vital need in fire-prone ecosystems worldwide (Aronson and Vallejo 2006). These tools also need to be explored to evaluate the effectiveness of pre- and post-wildfire forest restoration treatments and assess the effect of recurrent fires and environmental conditions on ecosystem dynamics.

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