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Influence of land-use types and climatic variables on seasonal patterns of NDVI in Mediterranean Iberian ecosystems

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Abstract

Question: What is the influence of management on the functioning of vegetation over time in Mediterranean ecosystems under different climate conditions?

Location: Mediterranean shrublands and forests in SE Iberia (Andalusia).

Methods: We evaluated the Normalized Difference Vegetation Index (NDVI) for the 1997-2002 time series to determine phenological vegetation patterns under different historical management regimes. Three altitudinal ranges were considered within each area to explore climate×management interactions. Each phenological pattern was analysed using time series statistics, together with precipitation (monthly and cumulative) and temperature.

Results: NDVI time series were significantly different under different management regimes, particularly in highly transformed areas, which showed the lowest NDVI, weakest annual seasonality and a more immediate phenological response to precipitation. The NDVI relationship with precipitation was strongest in the summer-autumn period, when precipitation is the main plant growth-limiting factor.

Conclusions: NDVI time series analyses elucidated complex influences of land use and climate on ecosystem functioning in these Mediterranean ecosystems. We demonstrated that NDVI time series analyses are a useful tool for monitoring programmes because of their sensitivity to changes, ease of use and applicability to large-scale studies.

Keywords: Autocorrelation; Cross-correlation; Human influence; Time series.

Introduction

Temperature and rainfall cycles condition the activity and physiological state of vegetation and, consequently, the spatial and temporal patterns (Badeck et al. 2004). Climatic variability in Mediterranean mountains leads to a characteristic phenological pattern with two dormancy periods, one in winter due to low temperatures, and another in summer due to reduced rainfall (Valladares 2004; Martínez-Alonso et al. 2007). Human activity, which is very common in Mediterranean ecosystems, imposes different footprints on these seasonal climate patterns. Human-induced changes in plant structure and dynamics strongly influence energy, water balances and carbon cycles, and in turn affect ecosystem dynamics and stability (Telesca & Lasaponara 2006). Since human activities severely modify the relationship between climate and plant activity, they must be taken into account in the study of ecosystem functioning, particularly in regions with long-term human interference in natural ecosystem processes. However, few studies have explicitly examined the effect of climate versus human intervention on vegetation dynamics (Herrmann et al. 2005).

One concern in environmental management is finding the repercussions of management regimes on the functioning of vegetation over time. The development of indicators sensitive to changes in vegetation cycles provides information on vegetation condition, functioning and response to natural and human perturbations. In this sense, remote sensing has produced a huge advance in the study and monitoring of vegetation, quantifying processes and temporal changes on relevant spatial scales (Running et al. 1995). Many vegetation indices have been developed and their qualities have been widely discussed (Banari et al. 1995). Among these indices, the Normalized Difference Vegetation Index (NDVI), which is sensitive to photosynthetic pigment content and vegetation condition and activity, is the most commonly used and is considered a good indicator

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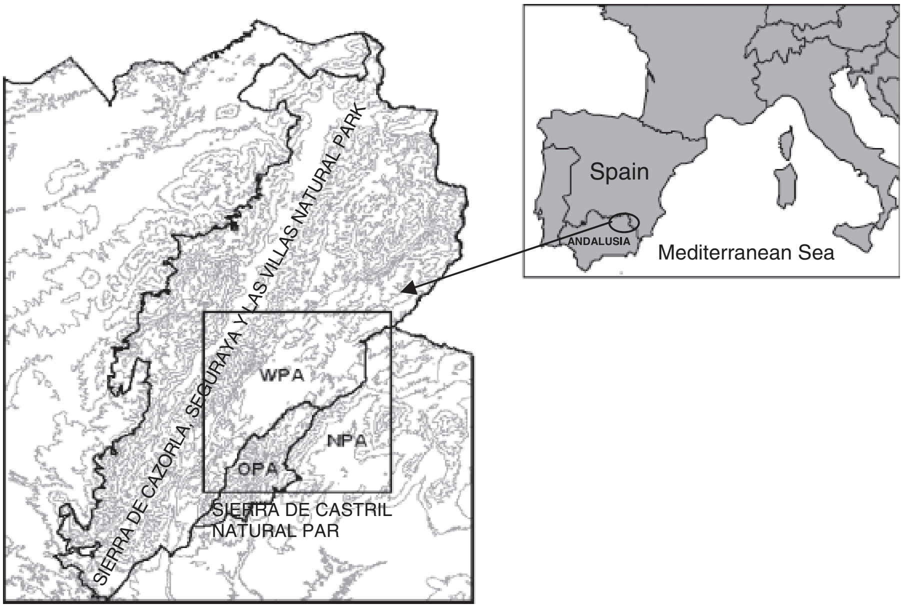


App. 1. Map of the study area in southern Spain, showing the three adjacent areas that differ in their level of protection and management regime. The borders of Sierra de Cazorla, Segura, Las Villas and Sierra de Castril Natural Parks are shown in the inset, together with elevation lines (WPA, well-protected area, OPA, overexploited protected area, NPA, non-protected area).

of vegetation response to environmental factors (Pettorelli et al. 2005). In fact, many studies using NDVI have identified key climate factors that control inter-annual variability in plant activity (Fang et al. 2001; Piao et al. 2006; Lloret et al. 2007). In arid and semiarid zones, such as those in the Mediterranean, where precipitation is the main plant growth- and production-limiting factor, rainfall use efficiency (understood as the quotient of NDVI and rainfall) has been widely used as an index of ecosystem degradation (Verón et al. 2006; Camberlin et al. 2007; Wessels et al. 2007).

The NDVI time signature, derived from satellite image sequences, provides specific information on seasonal patterns in different plant communities (Maselli 2004; Ivanova et al. 2007). This is crucial for analysis of not only the phenological response of vegetation to climate change (Peñuelas et al. 2004), but also for establishing long-term tendencies and identifying shifts in function resulting from changes in management.

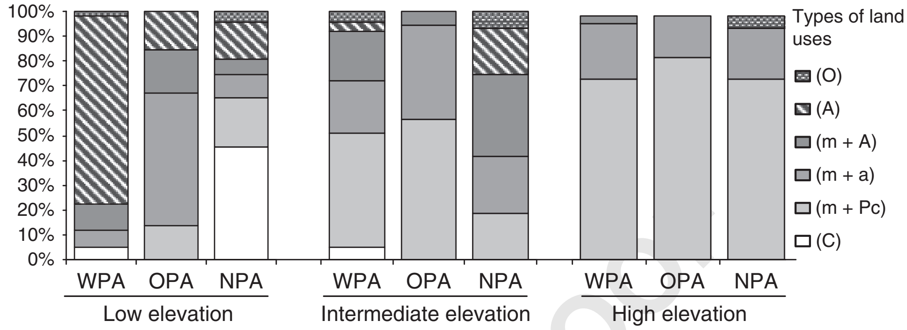
Our aim was to demonstrate the influence of land-use types (resulting from different historical management regimes) and climate on the seasonal pattern of NDVI in three different areas. We argue that any factor leading to an alteration of land use or cover will modify its seasonal pattern. When these alterations appear, the ecosystem loses its ability for self-regulation and, consequently, its stability (Vázquez 1993). The less altered ecosystems can be expected to buffer the effects of climate stochasticity as a consequence of better conditions for water retention (Goward & Prince 1995). So we hypothesize that least altered ecosystems will have the most stable seasonal NDVI patterns over time. This is supported, for instance, by studies exploring the impact of grazing on seasonality, stability and productivity of rangelands in arid zones (Oba et al. 2003).

Materials and Methods

Three adjacent areas (71 550 ha) were identified in northeast Andalusia, Spain (App. 1).[1] These are characterized by complex valley-and-peak relief, with an altitude ranging from 700 to 2350 m, and a typical Mediterranean climate of dry and hot summers (Table 1). The dominant vegetation is pine and oak woodland, mixed with various Mediterranean shrubland communities. The areas have comparable topography, climate and potential vegetation, but have different historical management regimes that have given rise to different combinations of land-use types (Consejería de Medio Ambiente 2007) in each one. Nine environmental units resulted from dividing the three areas (land management zones) into three elevation zones, based on the classification proposed by Rivas-Martínez (1996): low (with driest and warmest conditions), high (wettest and coldest

Table 1. Elevation (m), temperature (°C) and precipitation (mm year $^{-1}$) variable range (and their means) characteristic of the nine environmental units defined by land management regime and elevation. *Mean annual temperature (1960-1990 time series) **Mean annual precipitation (1960-1990 time series).

Bioclimatic zone/management type	Low elevation			Intermediate elevation			High elevation		
	Elevation	T*	P**	Elevation	T	P	Elevation	T	P
Well-Preserved Protected Area (WPA)	700-1300 (1054)	12-16 (13.8)	650-1250 (928)	1300-1850 (1593)	9-12 (10.8)	700-1400 (1041)	1850-2050 (1900)	8-10 (10.7)	1000-1300 (1037)
Overexploited Protected Area (OPA)	900-1300 (1171)	12-15 (13.1)	650-900 (784)	1300-1850 (1615)	10-12 (10.7)	800-1200 (994)	1850-2100 (1924)	8-10 (10.5)	1050-1250 (1011)
Non-protected Area (NPA)	950-1300 (1174)	12-15 (13.2)	300-800 (572)	1300-1850 (1549)	10-12 (11.1)	500-1050 (796)	1850-2350 (1955)	7-10 (10.9)	900-1150 (810)



App. 2. Percentage of types of land use within each of the nine environmental units defined by land management regime and elevation. Protection and management regime: WPA, well-protected area; OPA, overexploited protected area; NPA, non-protected area. Types of land use or land cover: C = Dry crops; A = Dense woodland; m+A = Scattered shrubland with dense woodland; m+a = Scattered shrubland with scattered woodland; m+Pc = Scattered shru-land with scattered grassland; O = Other land uses.

conditions) and intermediate. The three areas were characterized as:

Well-preserved protected area (*WPA*): in the Sierra de Cazorla, Segura y Las Villas Natural Park. Although livestock are still extensive within the area, its main use is for forest harvesting. This area was taken as the study base reference because of the good conservation status of the vegetation and excellent management practices (Valle et al. 1989; Araque 1997). Historical management has permitted a combination of land-use types close to the potential vegetation maxima: low elevations are dominated by dense, biologically diverse coniferous forest (*Pinus*) covering 80% of the zone; at intermediate elevations, shrubland covers 90%, mainly mixed with grassland; and high elevations are dominated (70%) by scattered shrubland with scattered grassland (App. 2).[1]

Overexploited protected area (*OPA*): located in the Sierra de Castril Natural Park. The main use of this area is for livestock, and, over the years, this has given rise to the current overgrazing status (Passera et al. 2001). The resulting land-use types are a combination of different Mediterranean shrublands (maccia) covering more than 80% of the whole area, mixed with scattered woodland or grassland (App. 2).[1]

Non-protected area (NPA): is adjacent to the two protected areas, but lacks any environmental conservation policies. In lowlands, about 50% of the zone has undergone intense human transformation for dryland crops. At higher altitudes the impact of agriculture decreases. At intermediate elevations, coniferous woodland covers 20% and scattered shrublands dominate the rest of the zone. At high elevations, as in the other areas, scattered shrubland with grassland constitute more than 70% (App. 2).[1]

Definition and calculation of variables

The phenological spectrum (monthly NDVI values), mean temperature (T) and precipitation (P) were calculated for each of the nine environmental units from April 1997 to September 2002. NDVI data were taken from the Indian Remote Sensing Satellite (IRS-1C/1D) Wide Field Sensor (WiFS) images, with a 180-m spatial resolution, and were processed by the Consejería de Medio Ambiente de Andalucía, following the same digital image processing protocol used in other studies (Consejería de Medio Ambiente 2003).

These images have proven enormously useful for studying processes related to phenological fluxes at local and regional scales (Roy & Joshi 2002). Every image was radiometrically normalized for sun elevation, Earth-Sun distance, and atmospheric conditions, geometrically corrected, and free of clouds, snow and water. Monthly synthetic stacks were generated from the NDVI maxima for each 30/31-day period in these corrected images. Monthly T and P were derived from 25 standard stations of the Spanish National Meteorological Institute and were pre-processed to fill any gaps. The point data were spatially interpolated with a local climate model to generate continuous information over a 20-m resolution digital elevation model. Multiple regression analysis was applied to the climate model, with longitude, latitude and altitude as independent variables. Every correlation equation was statistically significant ($P < 0.05$). The data were then rescaled to 180-m grid cells to match the NDVI data.

The monthly spatial average of the three variables (NDVIm, Tm and Pm) was calculated for each environmental unit, using only pixels entirely contained within that unit (400 pixels in the smallest unit and 13 000 in the largest).

Time series processing

To characterize the phenological pattern in each environmental unit, a widely used method was applied based on mean monthly NDVIm profiles (Telesca & Lasaponara 2006; Ivanova et al. 2007). NDVIm time profiles were averaged over the 6-year period, resulting in a 12-month function with mean values for each month. The same procedure was followed to calculate the Tm and Pm annual trends.

Time pattern stability, understood as the repetition of a pattern over time, was explored using an autocorrelation function (ACF), which measures the correlation between time observations that are separated by different distances. The ACF is formally defined as correlational dependency of k order between each ith element in the series and the $(i-k)$th element (Kendall 1984). It gives an indication of the association between variables Y_t and Y_{t-k} where the time lag k is 1, 2, 3, etc, for half of the elements in the series, at most (Box et al. 1994; Chatfield 2003). In our case, the maximum time lag order was a quarter of the observations (15 months). We plotted ACF correlograms (autocorrelograms), showing the correlation coefficients graphically and numerically, with 95% confidence intervals and significance of $P = 0.05$ for consecutive lags.

To analyse climate influence on vegetation phenological patterns, Tm and accumulated Pm time series (accumulated in the same month, P.0; or during i months before, $\Sigma P - i$) were related to NDVIm. After exploration of the NDVIm time series, the series were divided according to the influence of climate on vegetation: winter cold (January-June) and summer drought (June-December). The relationships of Tm and Pm to NDVIm were examined by cross-correlation analysis.

Time series, after normalisation and standardization, were analysed with Brodgar v.2.5.0 software (Highland Statistics Ltd, 2000; Newburgh, Aberdeenshire, UK), which was designed for use in environmental research with short multifactor time series.

Results

Phenological patterns and intra-annual variations

Mean monthly NDVIm described a double peak pattern typical of Mediterranean ecosystems (Fig. 1): spring growth (green wave) from March/April, to a greenness peak in June, decreasing in the summer months until August, recovering again (brown wave) to arrive at a second greenness peak in autumn (October/November). The profiles for each of the nine environmental units differed over the seasons. In the low-mountain zone, WPA had the maximum NDVIm and the widest range (from 0.70 to 0.52), while NPA had the lowest values and least variation (from 0.33 to 0.28). At higher altitudes, the NDVIm profiles were more uniform across land-use types, smoothing out the second peak in the high-mountain zone, OPA had the lowest NDVI peak (0.32) and the shortest range (0.09), while WPA and NPA had larger values of both maxima (0.37 and 0.39, respectively) and range of variation (0.11 and 0.12, respectively).

Inter-annual variation of phenological patterns

The NDVI time series described periodic patterns in which the inter-annual stability varied with historical management regime and altitude (Fig. 2). In the low-mountain zone, the WPA autocorrelogram showed inverse behaviour every 6 months (correlation −0.38) and marked annual behaviour (12-month autocorrelation of 0.52). In the OPA

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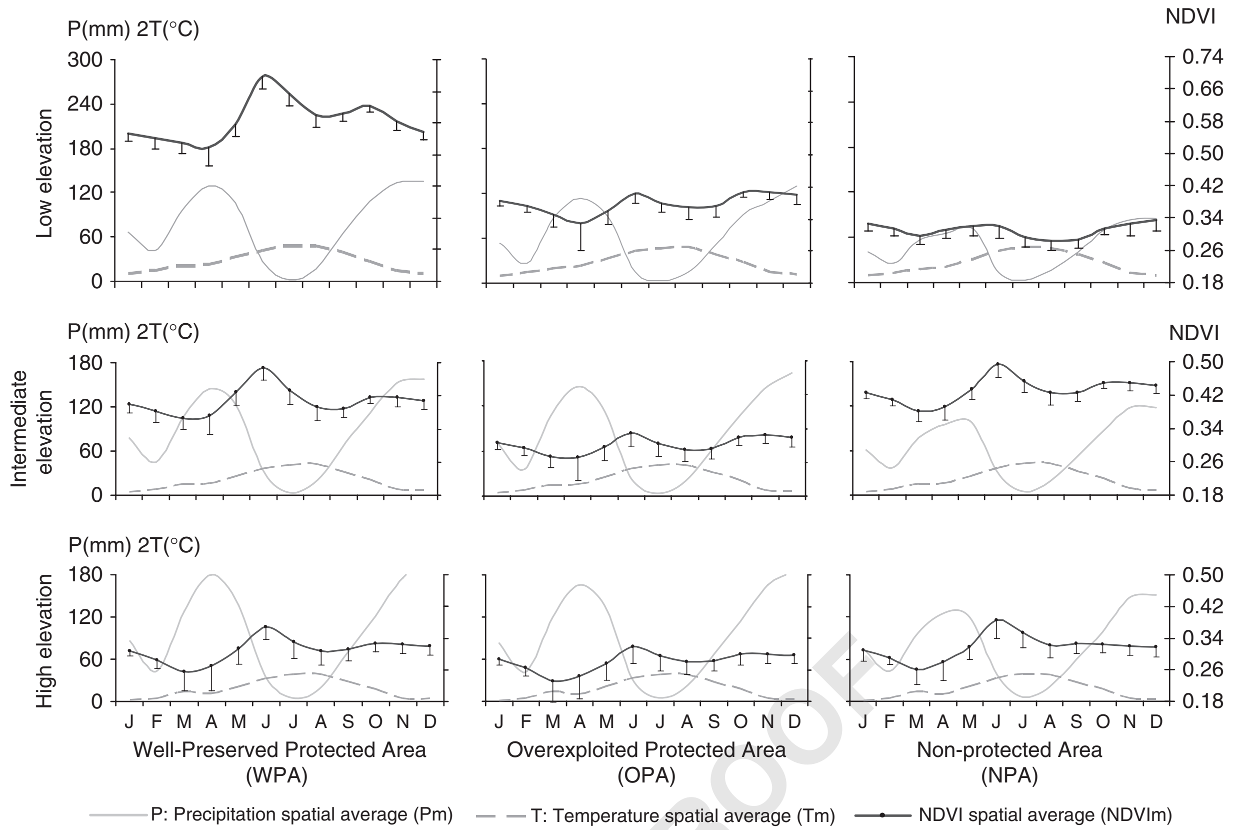

Fig. 1. Annual NDVI profiles (NDVIm), temperature (2Tm) and precipitation (Pm,) for the nine environmental units defined by land management regime and elevation. Values are means for the 1997-2002 period. Error bars for NDVI indicate one-third of the coefficient of variation.

autocorrelogram, weaker annual seasonality was observed (correlation 0.35 for a lag of 12 months), and in NPA a single negative correlation ($-$ 0.31) was observed every 9 months. In the intermediate elevation zone, the WPA and NPA autocorrelograms had very similar shapes, with single significant annual correlations (0.52 and 0.56, respectively). In the OPA autocorrelogram, there were significant values for a lag of 6 months (0.30) and 12 months (0.33). As altitude increased, the autocorrelograms became more homogeneous, showing strong annual seasonality in the three areas (0.51, 0.50 and 0.56 for WPA, OPA and NPA, respectively).

Influence of climate on phenological patterns

Tm and Pm profiles had very similar patterns in all environmental units, varying only quantitatively with elevation (Fig. 1): hot, dry summers (23.7°C and 2.4 mm in July and August) and cold, rainy winters (0.6°C and 85.5 mm in January). A drought period was observed in each graph from June to August/September, understood as the length of time when precipitation (mm) is less than double the temperature (°C) (Gaussen 1955). The Tm and Pm autocorrelograms were calculated in every elevation zone, showing a total absence of significant precipitation cycles, but very stable temperature cycles (6-month autocorrelation of $-$0.89, and 12-month autocorrelation of 0.9).

Correlation analysis between the complete NDVIm series and the climate variables (Table 2), calculated by cross-correlation function (CCF), showed a positive significant correlation for Tm only at low and intermediate elevations in WPA, and at intermediate and high elevations in NPA. The correlations for precipitation were fewer than expected. Significant correlations from monthly (P.0) to 3-month cumulative precipitation (ΣP-3) were found at low elevations in NPA (maximum correlation in ΣP-2, 0.52), where annual rainfall was lowest. In the other areas, when rainfall was not as limiting, the correlations were lower or even disappeared. In all areas, correlations were higher for the main growth periods than for the entire year. NDVIm had a significant correlation for different

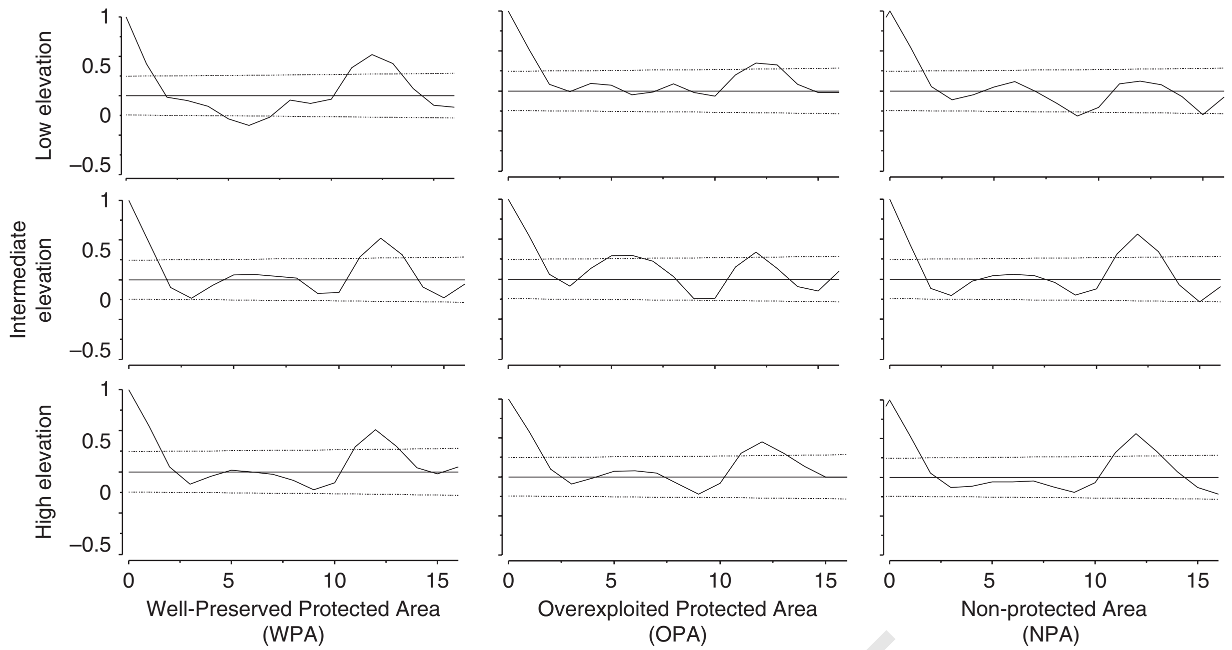

Fig. 2. Time autocorrelograms of mean NDVI (NDVIm) for 1997-2002 for the nine environmental units defined by land management regime and elevation. Thin, horizontal lines show significant correlation limits (95% confidence level), consequently, NDVI values outside these bands exhibit a significant autocorrelation for those time intervals.

climate variables, depending on the period: only with temperature from January to June (data not shown), and primarily with precipitation from June to December (Table 3). In the June-December period, the shortest response to precipitation was at low elevations, where NPA showed a significant correlation with P.0 and a maximum (0.65) for ΣP-2. However, WPA showed a delayed response of vegetation for 2- to 4-month cumulative precipitation and a maximum correlation for ΣP-3 (0.55). At intermediate elevations, the shortest response was observed in OPA (ΣP-1). At high elevations, although WPA and OPA had the same immediate response, WPA had a maximum in ΣP-2 and ΣP-3 (as in NPA), while OPA had a maximum in ΣP-2.

Discussion

Analysis of NDVI time series depicted changes in vegetation phenological cycles associated with elevation and with different land-use types. In most studies phenological changes are related to climatic variables, and are applied to evaluate vegetation condition (Maselli 2004; Volcani et al. 2005) or predict responses to climate variation (Zhang et al. 2003; Tadesse et al. 2005; Lloret et al. 2007). However, as detected in this study, these climate-driven changes are influenced by historical land management regimes, which are of key importance in the Mediterranean region. The relationship between land use and the NDVI time series has not been amply documented, even though it is crucial for interpreting the influence of land-use management on the functioning of natural species.

Differences in synchrony between the phenological patterns of vegetation and the climate cycles were associated with differences in land-use type, which arose from historical differences in land management. The different land-use types occupy adjacent areas with homogeneous conditions of topography, climate and potential vegetation. In land-use types with the strongest human intervention (NPA and OPA), this synchrony was less apparent, as reflected both in the variation in mean NDVI profile at an annual scale (Fig. 1) and in the inter-annual stability of this pattern (Fig. 2).

At low elevations in WPA, where dense conifer forest dominates (App. 2),[1] the seasonal profile agreed with the general temperature and rainfall regimes, with maximal range of variation in the growing periods, and strong inter-annual stability. On the other hand, in OPA, where the dominant land cover is shrublands with scattered stands of trees, the phenological pattern showed smaller seasonal differences and a smaller range of variation, although it also had annual stability. In NPA, where

Table 2. Coefficients of correlation (lag = 0*) using the cross-correlation function between complete series of NDVIm with temperature (*T*) and precipitation for the nine environmental units defined by land management regime and elevation. The grey boxes show a positive significant correlation ($P < 0.05$). *Only results for lag 0 were statistically significant; **Monthly precipitation, P.0; and cumulative precipitation during i months before, $\Sigma P - i$

Management type/ bioclimatic zone	Well-preserved protected area (WPA)						Overexploited protected area (OPA)						Non-Protected Area (NPA)					
	T	Precipitation**					*T*	Precipitation					*T*	Precipitation				
		P.0	P − 1	ΣP − 2	ΣP-3	ΣP-4		P.0	P − 1	ΣP−2	ΣP−3	ΣP−4		P.0	P − 1	ΣP−2	ΣP−3	ΣP−4
Low elevation	0.53	− 0.15	− 0.06	0.02	−0.06	− 0.19	− 0.04	0.02	0.07	0.13	− 0.01	− 0.23	− 0.37	0.26	0.43	0.52	0.39	0.21
Intermediate elevation	0.28	0.01	0.21	0.31	0.20	0.00	− 0.06	0.07	0.30	0.39	0.23	0.02	0.28	− 0.01	0.14	0.22	0.09	− 0.10
High elevation	0.23	− 0.01	0.15	0.17	0.01	− 0.20	0.12	− 0.01	0.16	0.20	0.03	− 0.18	0.39	− 0.08	0.11	0.10	0.10	− 0.05

dry crops predominate, the phenological pattern was not in agreement with the expected seasonal climate phases. This was the area with the lowest NDVI values (Fig. 1) and least intra-annual variability in the mean annual NDVI profile, losing, in addition, its inter-annual stability.

At intermediate elevations, the pattern of land-use types across the different historical management areas is more uniform, and trees are, in general, substituted by shrubs (App. 2).[1] This resulted in similar phenological patterns across the areas that remained very stable throughout the year. OPA, with obvious overgrazing problems (Passera et al. 2001), had the lowest NDVI and the least regular annual behaviour.

At high elevations, the restrictive climate conditions and a decrease in anthropogenic activities were associated with fewer fluctuations in NDVI. In this elevation zone, the land-use types in the three areas were relatively uniform, mostly shrubs with scattered grassland. These land-use types showed similar phenological patterns, with very restricted and rather simplified seasonal phases: a tendency to a single greenness peak in late spring/early summer, with limited growth in autumn.

Our results show that historical land management and associated types of land use are strongly associated with phenological responses, altering the relationships between phenological patterns and specific climate variables. However, we observed no conclusive correlation of NDVI values with either monthly or cumulative precipitation (Table 2). Our results reveal that in Mediterranean mountains, NDVI is related to precipitation in the dry period, when rainfall becomes the limiting factor for plant growth (Table 3), but not in the winter-spring period, when temperatures are limiting, and there was a significant correlation only with temperature (data not shown). Therefore, phenological patterns are synchronized with the periodicity of the limiting climate factor(s) (Wang et al. 2001). These results agree with studies in which inter-annual variation of NDVI in unaltered vegetation was mainly controlled by water availability during the earliest months and in the dry season (Maselli 2004). Interestingly, the vegetation response to precipitation over the dry period exhibited different delays, depending on the combination of land uses: from almost no delay in highly transformed areas, to a 2- to 4-month lag response in well conserved areas. At higher altitudes, in general, OPA responded faster to precipitation than the other two types.

[1]See journal's electronic archive.

Table 3. Coefficients of correlation (lag = 0*) using the cross-correlation function between NDVIm with temperature (*T*) and precipitation for the nine environmental units defined by land management regime and elevation, from June to December. The grey boxes show a positive significant correlation ($P<0.05$). *Only results for lag 0 were statistically significant **monthly precipitation, P.0; and cumulative precipitation during *i* months before, $\Sigma P - i$.

Management type/ bioclimatic zone	Well-preserved protected area (WPA)						Overexploited protected area (OPA)						Non-Protected Area (NPA)					
	T	Precipitation**					*T*	Precipitation					*T*	Precipitation				
		P.0	P − 1	ΣP − 2	ΣP − 3	ΣP − 4		P.0	P − 1	ΣP − 2	ΣP − 3	ΣP − 4		P.0	P − 1	ΣP − 2	ΣP − 3	ΣP − 4
Low elevation	0.30	−0.15	0.20	0.46	0.55	0.36	−0.33	0.22	0.36	0.41	0.25	0.02	−0.48	0.38	0.53	0.65	0.52	0.28
Intermediate elevation	0.14	0.02	0.32	0.60	0.63	0.46	−0.18	0.13	0.46	0.67	0.56	0.33	0.07	0.04	0.23	0.47	0.45	0.30
High elevation	0.11	0.11	0.33	0.53	0.49	0.31	−0.03	0.15	0.35	0.50	0.41	0.23	0.36	−0.09	0.15	0.41	0.44	0.38

Our methods for analysing phenological patterns can be used for monitoring environmental status and trends in ecosystem processes. Similar approaches have been used to examine the diversity of ecosystems – from cold and wet to warm and dry – (Hoare & Frost 2004; Kovàcs 2007), demonstrating that phenology-based approaches are sensitive to transformation of land cover under different climate conditions and management regimes. The sensitivity to change and the speed of its determination, make remotely sensed phenological parameter data ideal as an indicator in surveillance programmes and especially in warning systems (Anderson et al. 2005; White & Nemani 2006). Thus, our findings, together with previous studies, reveal that relevant changes in a wide range of ecosystems can be easily and rapidly quantified by this approach, and conclusions obtained on an appropriate spatial scale can rapidly be transferred to managers and decision-makers.

Conclusions

The synchrony of the seasonal vegetation pattern with climate differed between the three areas, depending on the type of land use. More degraded or heavily transformed ecosystems showed more limited periods of growth and less stable patterns over time. Furthermore, synchrony of the pattern with the limiting climate factor was found to be more direct (less delay) in poorly conserved ecosystems, which suggests that these ecosystems have fewer mechanisms for short-term buffering of climate stochasticity.

Application of the easily acquired and interpreted NDVI time series data allowed detection of changes in phenological patterns associated with land management regimes and their modulation by climate. Given its low cost, wide spatial extent and sensitivity to key environmental variables such as those explored here, NDVI time series analysis should be included in monitoring programmes for natural and protected areas, especially in those that pursue sustainable management of natural resources.

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