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Satellite-Based Monitoring of Ecosystem Functioning in Protected Areas: Recent Trends in the Oak Forests (*Quercus pyrenaica* Willd.) of Sierra Nevada (Spain)

M.A. Dionisio, D. Alcaraz-Segura and J. Cabello
Andalusian Center for the Assessment and Monitoring Global Change (CAESCG)
Dept. Plant Biology and Ecology, University of Almería
Spain

1. Introduction

The implementation of monitoring and early warning programs on the ecological status of natural areas is increasingly recognized as an environmental priority (Lovett et al., 2007). However, the development of such programs faces important challenges derived from the many requirements that ecological indicators should fulfill to achieve effective monitoring and alert systems (Oyonarte et al., 2010). Nowadays, ecosystem functioning characterization has become crucial for the monitoring and management of ecosystems due to several reasons (Cabello et al., 2008). First, the evaluation of functional features of ecosystems, such as the carbon gains dynamics, complements the traditional description of ecosystems based solely on vegetation structural features (like physiognomy, dominant species, or floristic composition) derived from few plot observations (Mueller-Dombois & Ellenberg, 1974; Stephenson, 1990; Alcaraz-Segura et al., 2009a). Second, ecosystem functional attributes show a much quicker response to environmental changes than structural ones (Milchunas & Lauenroth, 1995; Wiegand et al., 2004; Alcaraz-Segura et al., 2008a). Third, functional traits are related to key ecological processes that provide a direct measurement of key ecosystem services (Oyonarte et al., 2010; Paruelo et al., 2011; Volante et al., In press). Finally, remote sensing tools can be used to monitor ecosystem functional attributes over extensive areas, in different regions, and with a fast-revisiting frequency (Paruelo et al., 2005; Pettorelli et al., 2005; Baldi et al., 2008; Cabello et al., 2008; Alcaraz-Segura et al., 2009a). The use of satellite-derived information allows for tracking the integrity of key ecological processes and their spatial and temporal variability with the advantage of using common protocols throughout the Earth (Dale & Beyeler, 2001). In this sense, several works have shown the ability of time-series of satellite images to assess the existence of long-term ecosystem functional changes both at the regional (Baldi et al., 2008; Alcaraz-Segura et al., 2010b) and local (Alcaraz-Segura et al., 2008a; Alcaraz-Segura et al., 2008b; Alcaraz-Segura et al., 2009b; Cabello et al., Accepted) scales.

Remote sensing tools can be used to detect both evident functional changes produced by land-use transformations (Volante et al., In press), and other subtle and less noticeable changes including insect outbreaks (Kharuk et al., 2003), wind (Yuan et al., 2002), droughts (Tucker & Choudhury, 1987) or floods (Sanyal & Lu, 2004), fires (Riano et al., 2002), pollution (Chu et al., 2003), etc. These impacts may derive in significant changes in key ecological processes, for instance, carbon balance, microclimate, and biodiversity patterns (Turner, 2005; Lovett et al., 2006; Perry & Millington, 2008). Remote sensing has been proved to be useful for monitoring this kind of "within-state" changes (Vogelmann et al., 2009). In particular, satellite-derived spectral vegetation indices, such as the Enhanced Vegetation Index (EVI) and the Normalized Difference Vegetation Index (NDVI), are considered the most useful approach to monitor ecosystem responses to environmental changes (Pettorelli et al., 2005). Vegetation indices constitute the most feasible approach to estimate primary production at the regional scale (Paruelo et al., 1997) since they show a linear response to the intercepted fraction of photosynthetically active radiation (FPAR) (Hanan et al., 1995), which represents the conceptual basis to relate vegetation indices with net primary production (NPP) through Monteith's model (Monteith, 1972) (equation 1).

$$NPP = PAR * FPAR * RUE \qquad (1)$$

Where NPP is the Net Primary Production, PAR is the amount of incident Photosynthetically Active Radiation, FPAR is the fraction of that PAR that is intercepted by vegetation green tissues, and RUE is the Radiation Use Efficiency that plants have to transform that radiation into organic carbon compounds. Given this direct relationship with NPP, the most integrative descriptor of ecosystem functioning (McNaughton et al., 1989; Virginia & Wall, 2001), vegetation indices are frequently used to derive indicators of ecosystem functioning such as the annual amount of carbon absorbed by vegetation, or the seasonality and phenology of the carbon gain dynamics (Pettorelli et al., 2005; Alcaraz-Segura et al., 2006).

To evaluate the usefulness of satellite-derived vegetation indices for monitoring functional changes within protected areas, we focused on the Sub-Mediterranean Pyrenean oak forests (*Quercus pyrenaica* Willd.) of the Sierra Nevada National Park (Spain). These forests are considered as a Natural Habitat of Community Interest (*Quercus pyrenaica* oak woods and *Quercus robur* and *Quercus pyrenaica* oak woods from Iberian northwestern, Directive 92/43/CEE) (García & Mejías, 2009). The Pyrenean oak forests are a *quasi*-endemic habitat of the Iberian Peninsula. The only non-Iberian representations are in the Central West of France and in the Rif Mountains of northern Morocco. In the South of Spain, the Pyrenean oak is considered as a vulnerable species (Blanca & Mendoza, 2000). Sierra Nevada oak populations are considered of great biogeographical importance since they constitute the southernmost Iberian representation of these forests (Molero et al., 1992) and they are considered relict deciduous forests in the Southern Mediterranean region (Blanca & Mendoza, 2000; Blanca, 2001). Several stands of these forests in the Sierra Nevada National Park have an unfavorable conservation status (Molero et al., 1992; Bonet et al., 2010). Multiple global change drivers have an impact on these southernmost woodlands of *Quercus pyrenaica* in the Iberian Peninsula. Historically, these populations have been subjected to intense human disturbances (logging, fires, grazing, agriculture, etc). As a result, these forests are highly fragmented and display low ecological maturity (García & Mejías, 2009) that threatens their long-term conservation. Currently, trends towards temperature rises and precipitation decreases have been hypothesized as the main constraining factor reducing

peripheral populations in Sierra Nevada National Park (Molero et al., 1992; Bonet et al., 2010). *Quercus pyrenaica* is a winter semi-deciduous tree with high water demand during the summer. Hence, the predicted lengthening of the summer dry period associated to a reduction in the annual precipitation and the increase in the mean annual temperatures (Bonet et al., 2010) could impose a serious challenge for the regeneration of these forests (Molero et al., 1992; Blanca & Mendoza, 2000). Unfortunately, compared to the wide availability of studies of forest ecology in Europe, there is an enormous lack of knowledge of the conservation status and ecology of Pyrenean oak woodlands in the Iberian Peninsula (García & Mejías, 2009).

Our objective in this study was to use a satellite-based approach to monitor changes in ecosystem functional attributes of the oak forests of the Sierra Nevada National Park (Figure 1). This approach is based on the characterization of the seasonal dynamics and the inter-annual variability and trends of the Enhanced Vegetation Index (EVI). From the mean annual curve of EVI of each forest patch, we derived functional attributes related to primary production, seasonality, and phenology of the forests. Finally, by contrasting the baseline conditions of each forest patch with the long-term observed trends for the period 2001-2009, we identified processes of functional changes happening in these forests that could guide management actions. We propose this satellite approach as a near-real-time tool to provide managers with ecologically meaningful assessments of the ecosystem status based on low-cost but effective information.

2. Methodology

2.1 The Pyrenean oak forests of Sierra Nevada National Park

Sierra Nevada National Park is located in the southeast of the Iberian Peninsula (Figure 1). This National Park protects the best samples of high and medium Mediterranean mountainous ecosystems (MMARM, 2004). This park is a hot spot for plant species richness (Blanca et al., 1998; Blanca, 2001) and invertebrate biodiversity. Its altitude (several summits over 3000 m.a.s.l.), its proximity to Africa, and steep altitudinal gradient constitute the main ecological and evolutionary factors determining its high biodiversity.

The Pyrenean oak forests (Figure 1) of Sierra Nevada represent a conservation priority for the Park managers. There are nine locations distributed on siliceous soils both in the northwestern and southern slopes of the mountain range. In general, they are associated to major river valleys and within an altitudinal range of 1200 to 1900 m.a.s.l. (Table 1).

2.2 Monitoring forest ecological status with EVI

Our monitoring approach was based on the characterization of ecosystem functional attributes derived from the seasonal dynamics of the Enhanced Vegetation Index (EVI). The EVI calculates the normalized difference in reflectance between the red light that is absorbed in photosynthesis and the strong reflection of near infra-red light caused by the cell structure of the leaves. It also includes a third wavelength (blue) that is used to correct the influence of the atmosphere and the soil. EVI is defined according to equation 2 (Huete et al., 1997).

$$EVI = G \frac{NIR - R}{NIR + C_1 R - C_2 B + L} \qquad (2)$$

Where NIR, R and B represent the reflectance in the near infrared, red, and blue wavelengths, C_1 (6) and C_2 (7.5) are coefficients of atmospheric resistance, G (2.5) is the gain factor, and L (1) is a soil correction factor.
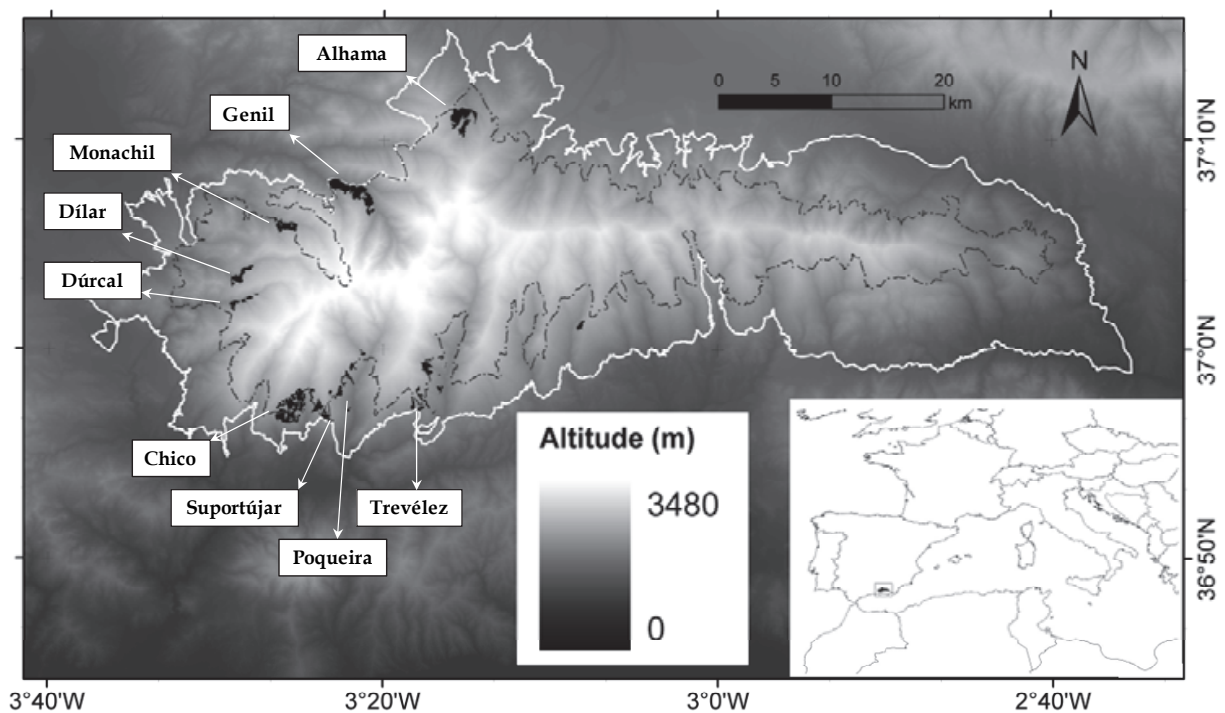

Fig. 1. Distribution of the Pyrenean oak forest patches (*Quercus pyrenaica*) in the Sierra Nevada National Park (southeastern Spain). Forest patches are named according the river basin where they are located: Alhama, Genil, Monachil, Dílar, and Dúrcal, in the northern slope; and Chico, Soportújar, Poqueira, and Trevélez in the southern slope.

Our approach uses satellite images of the Enhanced Vegetation Index captured by the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor onboard the Terra satellite from 2001 to 2009 (Product MOD13Q1). These images have a temporal resolution of 16 days (23 images per year) and a spatial resolution of 231x231 m. We used the Quality Assessment information to filter out low quality data, submitting images to a purification process which removes those pixels affected by high aerosol content, clouds, snow, shadows, and water. From this dataset, we first calculated the 9-year mean EVI seasonal curve for each oak forest site (Figure 1). For this, we only used pixels with more than 75% of their surface occupied by oak woods. Then, the following descriptive attributes of the ecosystem functioning were derived (Figure 2): The EVI annual mean (EVI_mean), an estimator of primary production; the EVI seasonal (or intra-annual) coefficient of variation (EVI_sCV), an indicator of seasonality of carbon gains; the EVI maximum (MAX) and minimum (MIN) values, indicators of the maximum and minimum photosynthetic capacities respectively; and the dates when the maximum (DMAX) and minimum (DMIN) EVI values are reached, two descriptors of the phenology of vegetation greenness. These attributes are widely used and have clear biological meanings (Pettorelli et al., 2005; Alcaraz-Segura et al., 2009a).

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To explore the existence of inter-annual trends of ecosystem functioning during the 2001-2009 period in the oak forests of Sierra Nevada, we followed the methodology suggested by Alcaraz-Segura et al. (2009b). In addition to the evaluation of long-term trends of the EVI_mean, we also evaluated the existence of significant trends within each of the 23 images (16-day periods) of the year by means of the Mann-Kendall trend test, a non-parametric trend test robust against non-normality, heterocedasticity, outliers, and serial dependence. For each pixel, we obtained the slope of the trends through the Sen's Method (Hirsch et al., 1982). Significant trends were considered with p-values < 0.05.
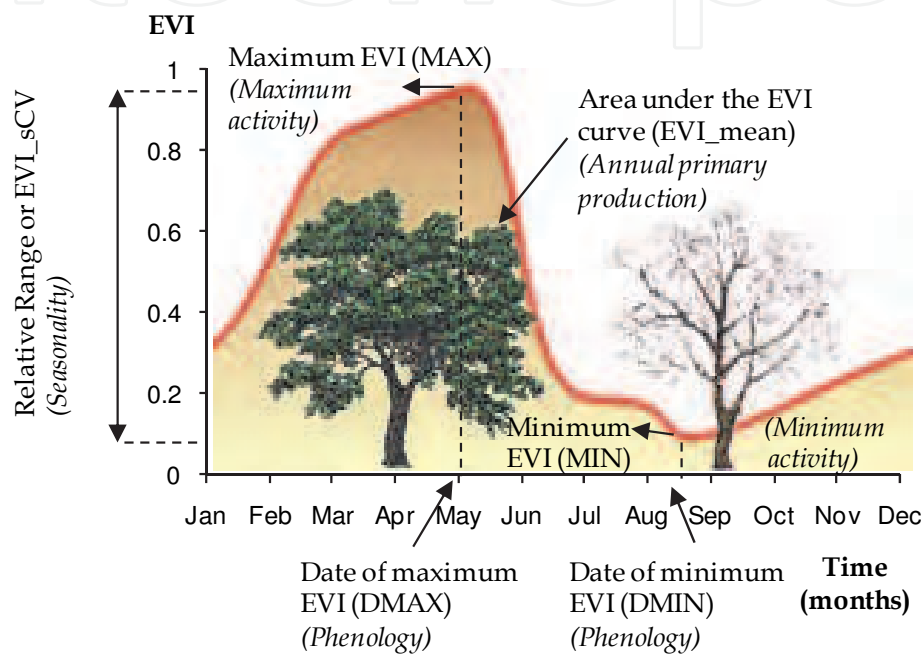

Fig. 2. Functional attributes of the EVI seasonal curve related to ecosystem primary production, seasonality, and phenology. EVI_mean: EVI annual mean, EVI_sCV: EVI seasonal Coefficient of Variation (SD/EVI_mean), MAX: Maximum EVI annual value, MIN: Minimum EVI annual value, DMAX: Date in which is reached the maximum EVI value, DMIN: Date in which is reached the minimum EVI value. These attributes have a clear biological meaning, the EVI_mean is an indicator of the fraction of the radiation used by plants and net primary productivity, MAX and MIN are indicators of the maximum and minimum photosynthetic activity, EVI_sCV is one indicator of seasonality of carbon gains, and DMAX and DMIN are indicators of phenology. Image modified from (Cabello et al., 2010) and G. Baldi from http://lechusa.unsl.edu.ar.

2.3 Statistical analyses

To evaluate whether there exist differences in the EVI attributes among the nine oak woods studied in Sierra Nevada, we performed analysis of variance (ANOVA) only when either raw or transformed attributes fulfilled the necessary parametric requirements of normality and homoscedasticity. To reach normality, for EVI_mean we applied a natural Logarithm (Ln) transformation (Shapiro-Wilk, W=0.990, p=0.266, n=177; Levene's Test F=0.474,

p=0.873, n=177) and for EVI_sCV a Box-Cox transformation (Shapiro-Wilk, W=0.983, p=0.031, n=177; Levene's Test F=1.951, p=0.055, n=177). The slight but not significant deviation from normality for the EVI_sCV data did not affect results. For those attributes that even transformed did not fulfill normality (MAX, MIN, DMAX, and DMIN), the analysis was conducted using the non-parametric Kruskal-Wallis test. To determine which groups significantly differed from each other, we used multiple *post hoc* comparisons, using the Tukey test for EVI_mean and EVI_sCV, and the Bonferroni test for MAX, MIN, DMAX, and DMIN. See Figure 5.

3. Results

3.1 Functional characterization of Sierra Nevada oak woods

The Pyrenean oak forests of Sierra Nevada showed a heterogeneous spatial behavior in terms of their EVI seasonal dynamics. In general, woods of the southern slope of Sierra Nevada displayed greater annual vegetation greenness and longer growing seasons than those from the northern slope (Figures 3 and 4). The seasonal EVI curve of the oak woods in the northern slope (Figure 3) showed a gradual increase in productivity that begins around March and that reaches its maximum peak in late May - early June (Figure 5e). Then, senescence takes place at a similar but slightly lower rate than growth. In contrast, the EVI curves of southern-slope woods (Figure 4) show a later but much steeper start of the growing season in late April - early May, reaching the EVI maximum value in June, as in the northern slope woods (Figure 5e). Then, EVI maintains a slowly decreasing plateau until around November, when a less pronounced end of the growing season than in the northern woods occurs.

Statistical comparisons of the EVI attributes (Figure 5) among oak woods also revealed the former differences. In general, Northern oak woods had significantly lower EVI_mean values than southern ones (ANOVA: F=33.56; p=0.0000; n=177; Figures 5a and 6a). Dílar woods (Figure 3d) showed the lowest values and Poqueira (Figure 4c) the highest. The EVI_sCV displayed greater values in the north than in the south (ANOVA: F=29.35; p=0.0000; n=177; Figures 5b and 6b) and a much greater dispersion of data in the north. Although MAX values (Figures 5c and 6c) showed significant differences between some oak woods (Kruskal Wallis: H=36.94; p=0.0000; n=177), there were no clear differences between the northern and southern woods. In general, Max values showed little inter-woods, but large intra-wood variation. We hypothesize that this larger intra-wood variation could be related to greater altitudinal range, such as in Alhama, Genil, Chico and Trevélez (Table 1). DMAX did not either significantly differ between the northern and southern woods, happening in May-June in all oak woods but coming about later with altitude. The increase of intra-wood variability with greater altitudinal variation was also observed in DMAX (Kruskal Wallis: H=64.61; p=0.0000; n=177; Figures 5e and 7a). Regarding MIN values, southern woods showed significantly higher values than northern woods (Kruskal-Wallis: H=126.05; p=0.000; n=177; Figures 5d and 6d), which is directly related to EVI_mean (Figures 5a and 6a) and EVI_sCV (Figures 5b and 6b). Contrary to DMAX, DMIN showed great variability both within and among woods (from November to April) (Figures 5f and 7b) (May-July), with earlier DMIN values in the northern woods than in the southern ones (Kruskal-Wallis: H=86.93; p=0.0000; n=177; Figures 5f and 7b).
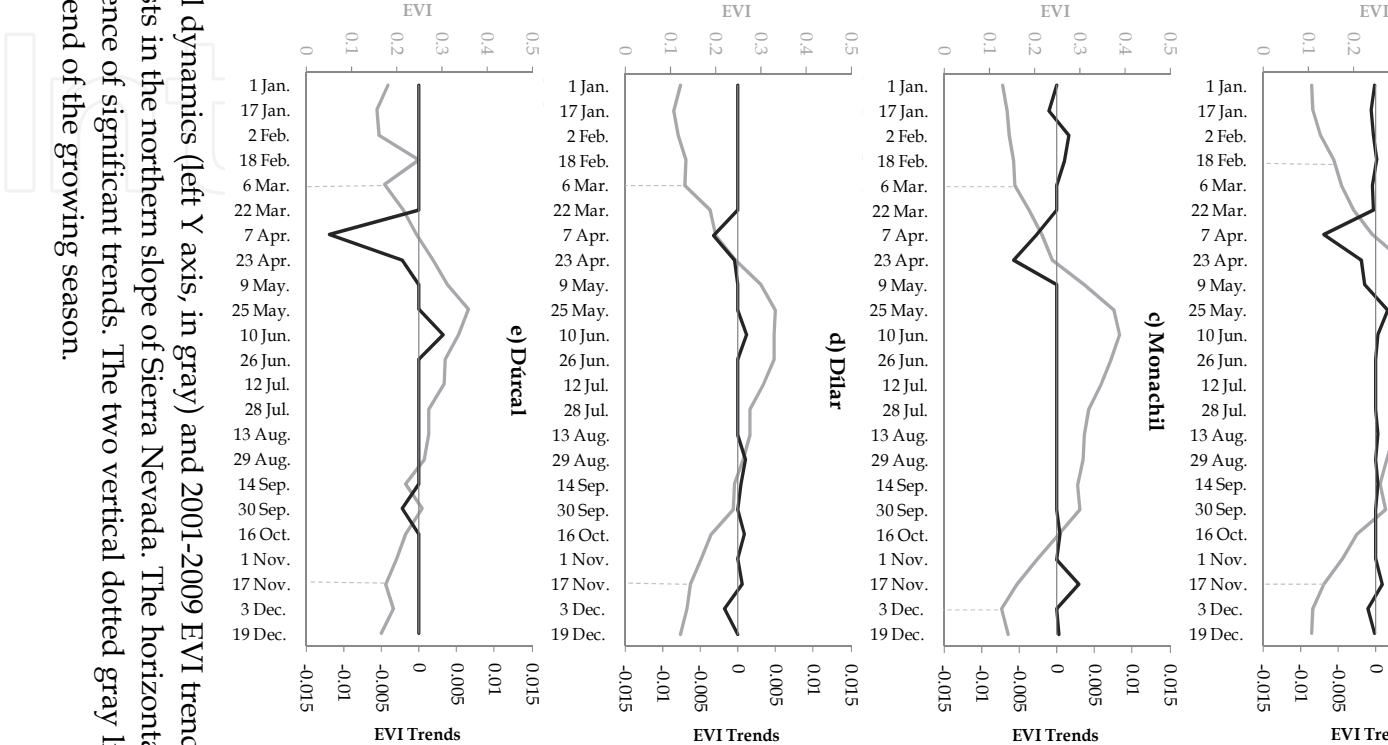
Fig. 3. EVI seasonal dynamics (left Y axis, in gray) and 2001-2009 EVI trends (right Y axis, in black) for oak forests in the northern slope of Sierra Nevada. The horizontal "zero-trend" line shows the absence of significant trends. The two vertical dotted gray lines show the beginning and the end of the growing season.
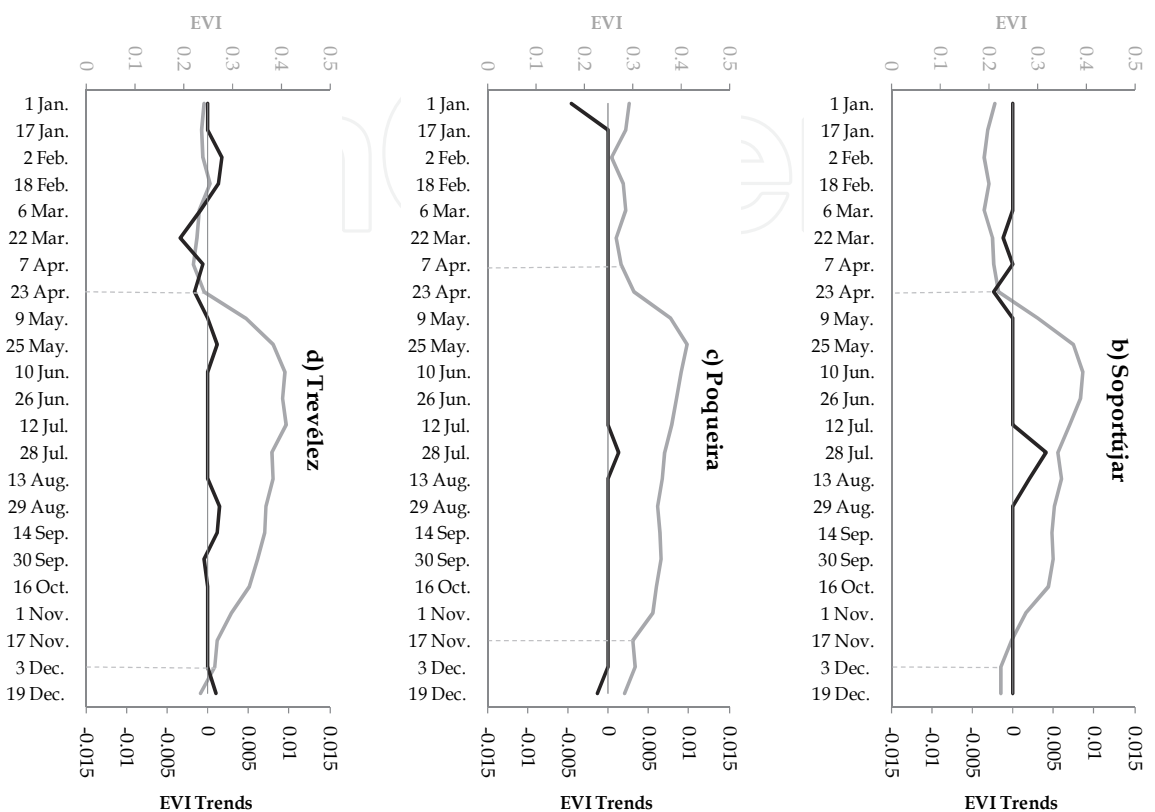
Fig. 4. EVI seasonal dynamics (left Y axis, in gray) and 2001-2009 EVI trends (right Y axis, in black) for oak forests in the southern slope of Sierra Nevada. The horizontal "zero-trend" line shows the absence of significant trends. The two vertical dotted gray lines show the beginning and the end of the growing season.

3.2 Functional changes in Sierra Nevada oak woods

We found significant functional changes happening in the Sierra Nevada oak woods during the 2001-2009 period. Though we did not observe significant long-term trends in the annual synthetic EVI attributes, particular periods of the year did show significant EVI trends. The greatest significant trends occurred at the beginning of the growing season, when strong EVI decreases were observed (March-April), particularly in the northwestern slope (Figure 3). A clearly marked downward trend in productivity was observed between 7th April - 23rd April), which took place in four out of the five northwestern oak woods (Genil, Monachil, Dílar, and Dúrcal, Figures 3b, 3c, 3d, and 3e). Alhama oak wood (Figure 3a) was the only exception, displaying no long-term trends. Some northern woods also showed small positive EVI trends in November (Genil, Monachil, and Dílar; Figures 3b, 3c, and 3d) and in the early-summer (Genil, Dílar, and Durcal).

The southern oak woods (Figure 4) also showed a decrease of vegetation greenness at the beginning of the growing season (except Poqueira, Figure 4c), but less deep than in the northern woods. In addition, EVI increases were observed in middle to late summer in three out of four southern woods (Soportújar, Poqueira, and Trevélez (Figures 4b, 4c, and 4d).

| Oak woods | Environmental traits | | | | # of pixels with EVI_mean trends | | |
	Area (ha)/ Pixels sampled (n)	Altitudinal range	Aspect	Slope	Positive Sen's slope (+)	Negative Sen's slope (-)	M-Kendall Significant (p≤0.15) (+/-)
Alhama	266/36	1443-1838	NE	25°	0	20	0/1
Genil	356/51	1272-1792	N	30°	0	29	0/14
Monachil	104/15	1630-1842	N	27°	0	8	0/1
Dílar	111/14	1594-1884	NW	31°	1	7	0/1
Dúrcal	58/4	1598-1833	W	28°	0	2	0/0
Chico	445/39	1459-1870	S	17°	1	21	0/9
Soportújar	46/4	1652-1755	SW	17°	1	1	0/0
Poqueira	105/5	1635-1888	SE	25°	1	2	0/0
Trevélez	167/9	1397-1880	E	24°	1	5	0/1

Table 1. Environmental traits and EVI_mean trends during the 2001-2009 period in nine *Quercus pyrenaica* oak woods of Sierra Nevada National Park. Forest patches are named according the river basin where they are located: Alhama, Genil, Monachil, Dílar, and Dúrcal, in the northern slope; and Chico, Soportújar, Poqueira, and Trevélez in the southern slope.
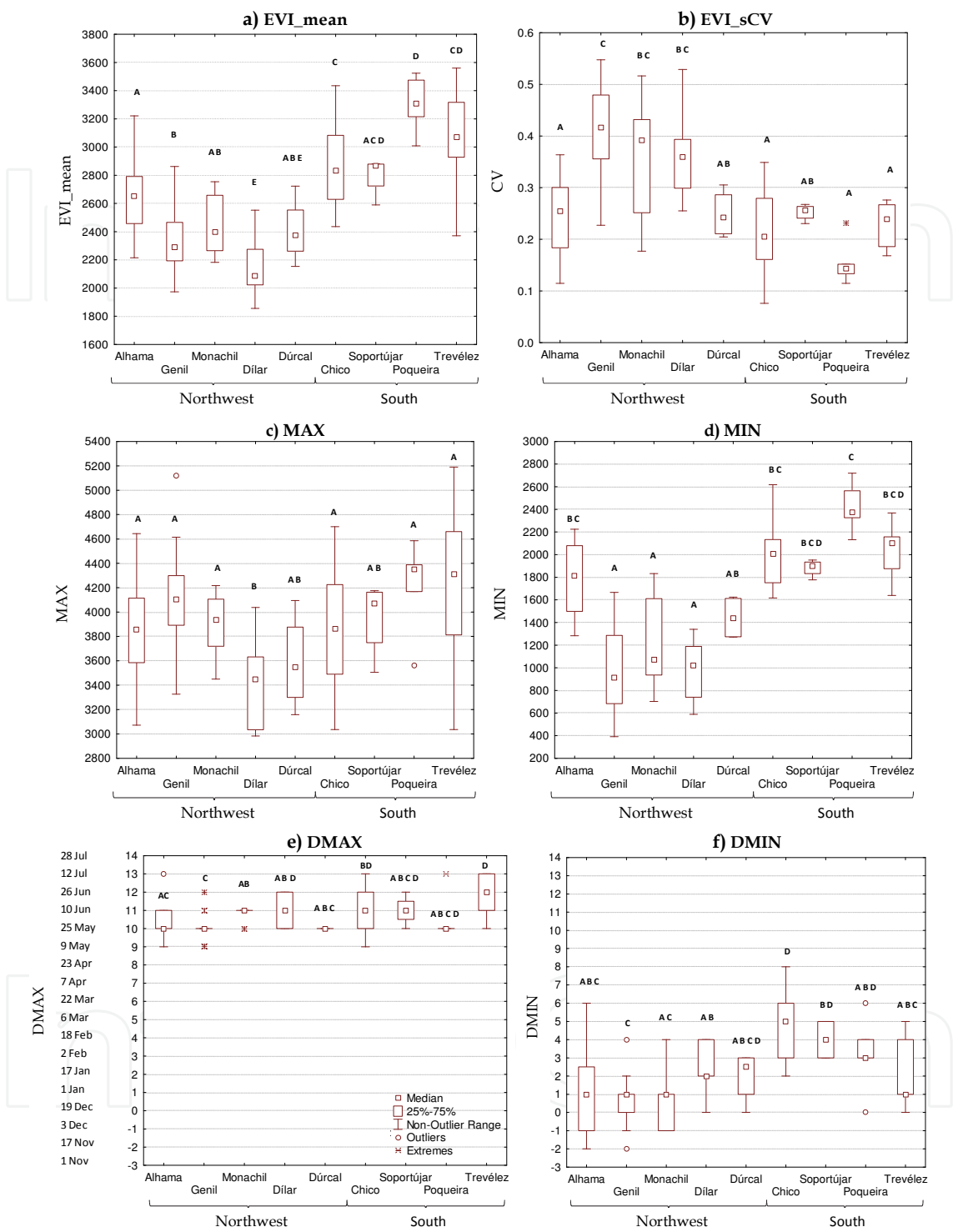
Fig. 5. Functional characterization of the oak woods of Sierra Nevada (Spain) based on the EVI attributes for the 2001-2009 period. Letters show significant differences in *post hoc* comparisons. a) EVI annual mean, an estimator of annual primary production; b) EVI seasonal Coefficient of Variation, a descriptor of seasonality; c) Maximum and d) Minimum EVI annual values, indicators of the maximum and minimum photosynthetic activity; Dates when the e) Maximum and f) Minimum EVI values are reached, indicators of phenology.

4. Discussion

4.1 Baseline conditions and trends in the ecosystem functioning of the Pyrenean oak woods of Sierra Nevada National Park

Our approach, based on a time series of satellite-derived images of the EVI, provided a description of how different attributes of ecosystem functioning change across the remaining locations of Pyrenean oak woodlands in Sierra Nevada. This reference description provides the baseline conditions of ecosystem functioning that can be used to assess the effects of environmental changes on ecosystems processes. The Pyrenean oak woodlands of Sierra Nevada showed a unimodal EVI seasonal dynamics with a unique and well-defined growing season centered in summer and winter minima, as observed in previous works (Alcaraz-Segura et al., 2009a). Differences among locations mainly occurred during the winter non-growing season and at the beginning of the growing season (spring) and were mainly related to the location in the north or south slopes of Sierra Nevada. The lower EVI_mean values in the northern oak woods (Figure 5a) are closely linked to the presence of lower winter MIN values than in the southern woods (Figure 5d) and with the more abrupt EVI decrease during the autumn. In contrast, southern woods maintained relatively high EVI values throughout their longer growing season (Figure 4). The greater annual vegetation greenness of southern woods is probably due to the greater incidence of solar radiation that favors longer growing seasons, milder temperatures during the winter, and an extra water supply from humid air masses coming from the Mediterranean sea that compensate the very high evapotranspiration rates during the summer, in comparison to the colder and more continental locations of the northern slope (Costa Tenorio et al., 2005). Contrary, summer maximum EVI values (MAX) would not cause significant differences in annual vegetation greenness between the northern and southern locations. In consequence, the northern slope shows much greater seasonality (EVI_sCV) than the southern slope since MAX values are similar in both orientations, though the northern woods showed lower MIN values than the southern ones (Figure 5d). From the analysis of the shape of the EVI seasonal curves and according to previous studies (Alcaraz-Segura et al., 2009a), the main limiting factors for vegetation greenness in the oak woodlands of Sierra Nevada are low winter temperatures and lower solar irradiation in the northern slope, which favors a longer presence of snow (Figure 5d). An important point to consider is that the greater vegetation greenness of the southern woodlands during the non-growing season is not related to the activity of the oak trees (because they are winter semi-deciduous), but to the shrubs and herbaceous vegetation occupying the undergrowth vegetation and the patches without trees (Figure 8). In the same way, since the snow melt happens faster and earlier in the southern woods, undergrowth vegetation is also responsible for the earlier and more pronounced rise in vegetation greenness during the start of the growing season than in the northern woods (Figure 3).

Our study also showed that though the oak woodlands of Sierra Nevada have not experienced significant changes of the EVI_mean during the 2001-2009 period, they have suffered seasonal functional changes that mainly affected the beginning of the growing season. In contrast to this relative stability of annual mean vegetation greenness (EVI_mean) since 2001, previous evaluations showed a significant increase in vegetation greenness throughout the eighties and nineties in Sierra Nevada (see Alcaraz-Segura et al., 2008b for the 1981-2003 period, and Alcaraz-Segura et al., 2009b for the 1982-2006 period). Such evaluations used the GIMMS-AVHRR (Global Inventory Modelling and Mapping Studies - Advanced Very High Resolution Radiometer) NDVI dataset. Though there is some debate on the existence of a long-term bias in the GIMMS dataset towards NDVI increases in some

regions of the world including the Canadian Boreal forest (Alcaraz-Segura et al., 2010a) and South America (Baldi et al., 2008), the NDVI increases observed in Sierra Nevada with GIMMS during the 1980's and 1990's agreed with other independent datasets. Alcaraz-Segura et al. (2010b) showed that the positive NDVI trends that Sierra Nevada displayed in previous studies with the GIMMS dataset were observed for the 1981-1999 period using other independent datasets such as PAL (Pathfinder AVHRR Land), FASIR (Fourier-Adjustment, Solar zenith angle corrected, Interpolated Reconstructed), and LTDR (Land Long-Term Data Record) datasets. Positive NDVI trends were also observed in Sierra Nevada during the 1989-2002 period using the MEDOKADS (Mediterranean Extended Daily One-km AVHRR Data Set) archive (Martínez & Gilabert, 2009).

The EVI decrease observed at the beginning of the growing season during the 2000-2009 period in Sierra Nevada oak woodlands (Figures 3 and 4), is also in contrast with the NDVI seasonal increase in autumn, winter, and spring that was reported for the 1982-2006 period using GIMMS images of the entire Park (see Figure 2 in: Alcaraz-Segura et al., 2008a). Such contrasting trends lead to think that the increase of spring vegetation greenness that occurred throughout de eighties and nineties (Alcaraz-Segura et al., 2008a) ended around the year 2000 when the spring started to return to lower greenness values. Yet, the trends towards greater vegetation greenness in autumn and winter reached during the eighties and nineties (Alcaraz-Segura et al., 2008a) was maintained after the year 2000, since we did not find significant EVI trends in these seasons. The strong EVI decreases at the beginning of the growing season and the presence of some EVI summer increases during the senescence period lead to think that the growing season of southern oak woods (Figure 4) might be starting later but strengthening towards the summer (with the exception of Poqueira; Figure 4c).

An important outcome of our work is that significant functional changes, i.e. a significant decrease of vegetation greenness at the beginning of the growing season, took place in Sierra Nevada oak woodlands without implying significant trends in the annual averages. Despite the EVI annual mean, an estimator of annual primary production, is extensively used as an integrative descriptor of ecosystem functioning and status, our work highlights the importance of studying variables beyond the annual summaries (like seasonality and phenology) as significant trends in particular months of the year may not significantly affect the EVI annual mean but may have broad ecological consequences in critical periods such as the start of the growing season.

4.2 Application to forest monitoring and management

Since satellite images are regularly captured over large regions and under common protocols, the spectral vegetation indices represent an adequate approach to implement ecosystems monitoring programs in protected areas and to promote adaptive management actions (Alcaraz-Segura et al., 2008a; Alcaraz-Segura et al., 2008b; Cabello et al., 2008). Our work provides interesting information for the prioritization and the orientation of management actions for the Pyrenean oak forests of Sierra Nevada National Park. First, we provided a regional functional reference characterization of all oak woodlands of the Park for the 2001-2009 period. Our monitoring approach uses EVI-derived descriptors of ecosystem functioning that may allow managers to detect the spatial and temporal anomalies (Oyonarte et al., 2010), and to guide specific management actions in particular areas. The spatial and temporal deviations from the baseline conditions detected could be alerting of inconspicuous "within-state" changes in the forests as a result of cumulative impacts (Vogelmann et al., 2009). However, to improve the ecological significance of this

approach for the Park management, the monitoring program should include the identification of the key ecological processes that can be related to this functional description and that are central for the maintenance of the ecological integrity. For instance, the differences in the strength of the EVI trends among different oak forest patches could be associated to the two modes of climatic variability that affect Sierra Nevada. The observed weaker start of the growing season during study period could be related to the increase of positive phases of the North Atlantic Oscillation (NAO Index), which are the main control of winter precipitation and temperature, particularly in the north-western slope (Liras, 2011). In addition, we also observed EVI increases during the summer (July-August) in the southern slope (Figure 4), which could be related to the increase of active phases of the Western Mediterranean Oscillation (WeMO), increasing late summer precipitation during the study period (Liras, 2011; Cabello et al., Accepted). In this sense, the obtained results in the EVI trends for the different woods could be used to prioritize management actions in relation to climate change adaptation in the most threatened sites. Nevertheless, this should be only one of the guiding hypotheses for adaptive management, since other processes such as insect damage and forest succession could also be taking place in the park (Sierra Nevada National Park managers, *personal communication,* Stöver et al., 1996; CMJA, 2008).

A monitoring system based on the tools and analysis shown here could embrace several monitoring objectives, as it simultaneously informs managers about the changes in productivity, phenology, and seasonality of the ecosystems. For example, changes in the EVI attributes could be directly related to changes in the amount, seasonality, and phenology of ecosystem carbon gains. In addition, linking the EVI dynamics of the Pyrenean oak woodlands to the ecology of species of conservation concern could be used to evaluate and monitor the conservation status of the habitat of such species. This could be the case of the blue tit (*Parus caeruleus*), whose reproductive success is related to the ecosystem status of *Quercus pyrenaica* forests, especially at the beginning of female reproductive period (April-May), which is associated with the start of the growing season (Arriero et al., 2006). Such association implies that delays in the start of the growing season or forest degradation would negatively affect the reproduction success of this bird. Moreover, the information derived from this monitoring approach could help guiding land-use planning to avoid overexploitation of Sierra Nevada oak woodlands. For instance, livestock pressure should be limited in those periods of the year that are experiencing strong negative EVI trends.

5. Conclusions

Our approach shows how satellite based monitoring systems can be very useful to assess the effects of environmental changes on protected areas and to orientate adaptive management actions. Overall, this study provides a reference characterization against which to assess changes in ecosystem functioning of the oak woods of Sierra Nevada, and identifies functional changes that occurred during the 2001-2009 period. Such information helps to fill the lack of knowledge about these woodlands, as demanded by the Spanish Ministry of Environment (García & Mejías, 2009). In practical terms, it allows the incorporation of ecosystem functional aspects of ecosystems to nature conservation and to the maintenance of ecosystem services, in particular those related to carbon sequestration in this protected area. Our results imply that conservation and management policies cannot be only based on static situations, since ecosystems are changing. In addition, annual summaries are not enough as monitoring indicators, since functional changes may occur at key seasonal stages without affecting the annual means.
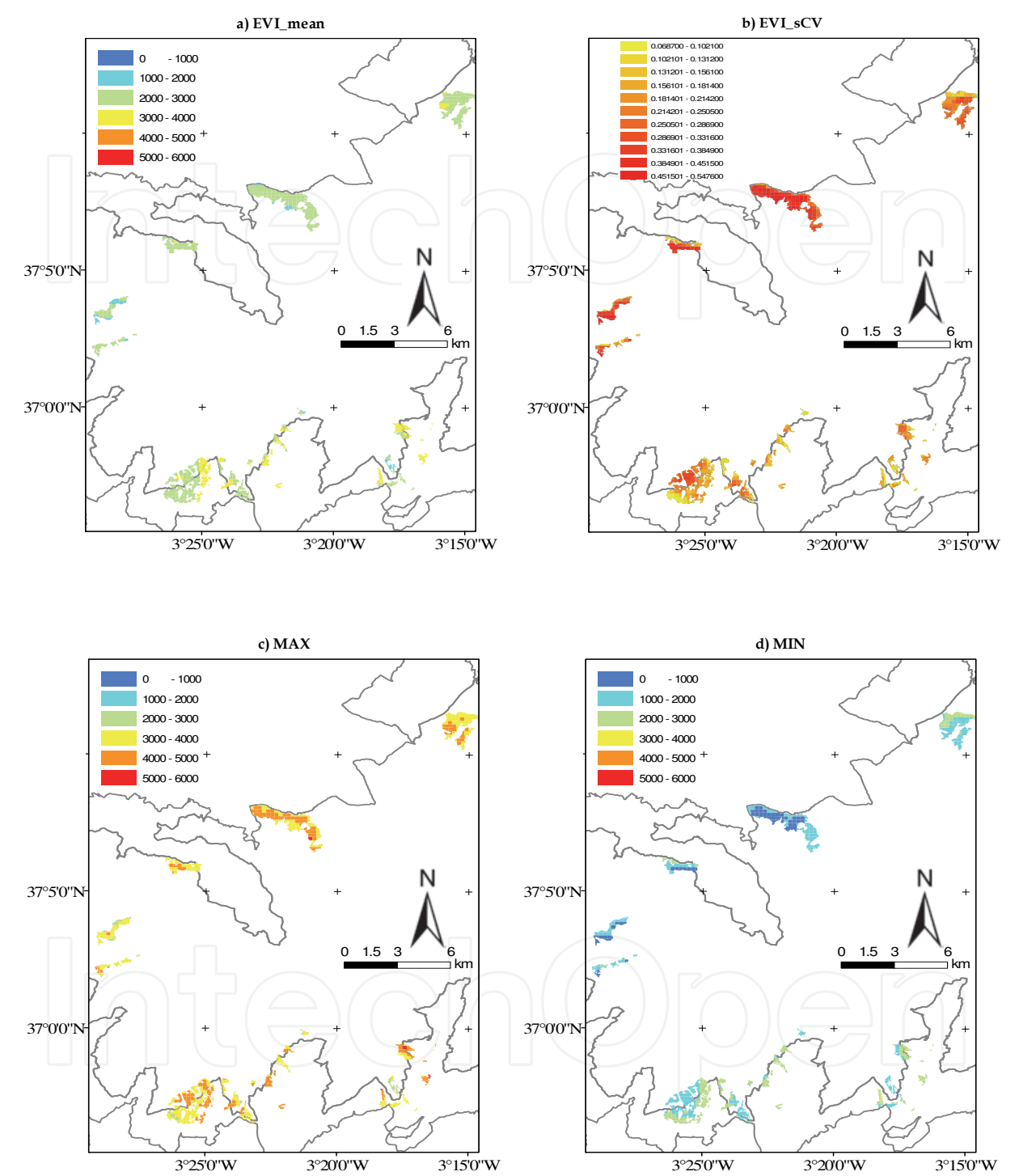
Fig. 6. Maps of the EVI attributes for Sierra Nevada Oak woods generated by the Monparq application. EVI_mean: EVI annual mean, an estimator of annual primary production; EVI_sCV: EVI seasonal Coefficient of Variation, a descriptor of seasonality; MAX and MIN: Maximum and Minimum EVI annual values, indicators of the maximum and minimum photosynthetic activity.
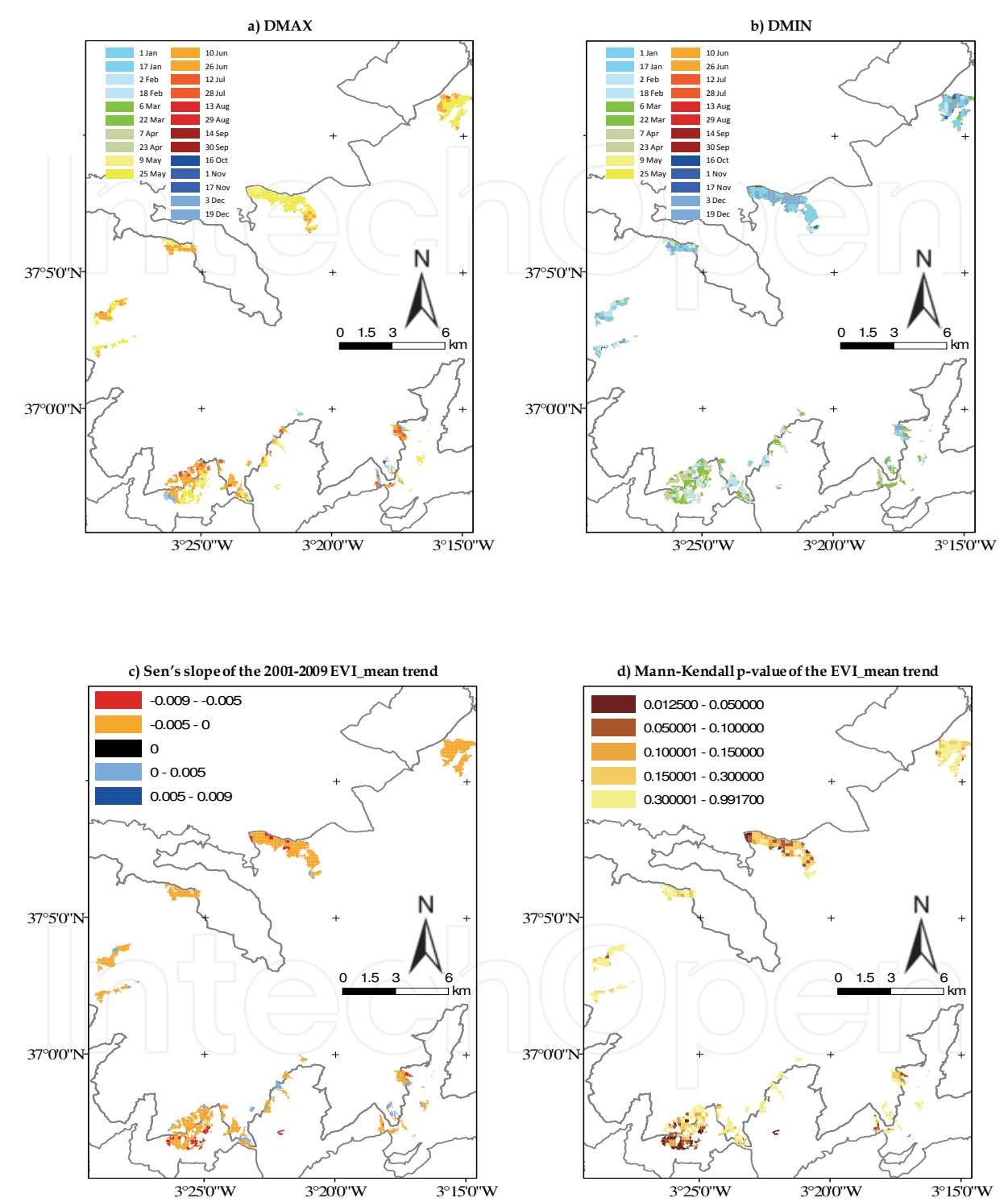
Fig. 7. Maps of the EVI attributes and trends for Sierra Nevada Oak woods generated by the Monparq application. a) DMAX and b) DMIN: Dates when the Maximum and Minimum EVI values are reached, indicators of phenology. c) Sen's slope of the 2001-2009 EVI_mean trend d) Mann-Kendall p-value of the 2001-2009 EVI_mean trend.

Fig. 8. Landscape picture showing the start of the growing season (13th April 2011) in the northernmost *Quercus pyrenaica* oak wood of Sierra Nevada National Park (Spain), the oak wood of the Alhama River at Dehesa del Camarate. The picture shows how the green sprouts of the oak trees are starting to come out while the leaves of the undergrowth shrubs are well developed.

To spread the use of our monitoring approach and to make possible for managers the exploitation of such information, we have developed a software tool named "Monparq Monitoring System for Parks" that allows a non-advance user to assess the differences between locations, to explore the different environmental controls across the northern and southern slopes, and to evaluate the inter-annual trends in ecosystem functioning. This tool provides managers with valuable information to assess management effectiveness in an adaptive management strategy. It will help managers answering questions like, what ecosystems are undergoing major changes?, or how do management actions affect ecosystem functioning stability?
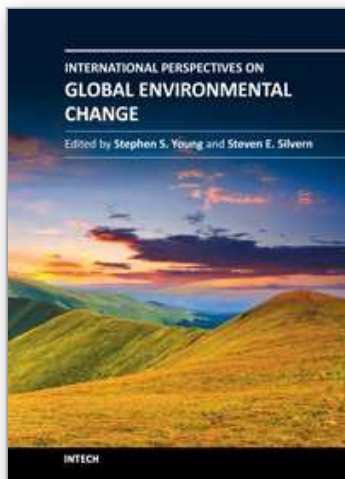
6. Acknowledgments

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