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# An estimation of the optimum temporal resolution for monitoring vegetation condition on a nationwide scale using MODIS/Terra data

**Shortened version of title:** Optimum temporal resolution for vegetation monitoring

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## Abstract

Monitoring vegetation condition is an important issue in the Mediterranean region, in terms of both securing food and preventing fires. The recent abundance of remotely sensed data, such as the daily availability of MODIS imagery, raises the issue of appropriate temporal sampling when monitoring vegetation: under-sampling may not accurately describe the phenomenon under consideration, while over-sampling, would increase the cost of the project without additional benefit. The aim of this work was to estimate the optimum temporal resolution for vegetation monitoring on a nationwide scale using 250m MODIS/Terra daily images and composites. Specific objectives included: (i) an investigation into the optimum temporal resolution for monitoring vegetation condition during the dry season on a nationwide scale using time-series analysis of NDVI dataset, (ii) an investigation into whether this temporal resolution differs between the two major vegetation categories, namely natural and managed vegetation, and (iii) a quality assessment of multi-temporal NDVI composites, following the proposed optimum temporal resolution. A time series of daily NDVI data was developed for Greece using MODIS/Terra 250m imagery. After smoothing to remove noise and cloud influence, it was subjected to temporal autocorrelation analysis, and its level of significance was the adopted objective function. In addition, NDVI composites were created at various temporal resolutions and compared using qualitative criteria. Results indicate that the proposed optimum temporal resolution was different for managed and natural vegetation. Finally, quality assessment of the multi-temporal NDVI composites revealed that compositing at the proposed optimum temporal resolution could derive products that are useful for operational monitoring of vegetation.

*Keywords*: time series; vegetation monitoring; temporal resolution; MODIS NDVI

## 1. Introduction

Condition of vegetation is a parameter of major importance in the Mediterranean region, as it is directly linked to the risk of natural vegetation catching fire and the productivity of agricultural crops. Monitoring vegetation is useful for international and national agencies that organize fire prevention plans, compensate for agricultural yield loss, and develop national policies. In Europe, such monitoring is dictated by a number of European and Council Regulations, such as 'Forest Focus' (2003/2152/EC), support system for producers of certain arable crops (1999/1251/EC), and support for rural development from the European Agricultural Guidance and Guarantee Fund (1999/1257/EC). Monitoring schemes on a nationwide scale for these operations can be very costly if based on field surveys, or very biased if based on secondary statistics (Biggs *et al.* 2006, Droogers 2002).

Since the early Landsat launches, satellite remote sensing has made an important contribution to vegetation monitoring, which has been further enhanced with the production of purpose-built instruments on board the latest platforms (Townshend and Justice 2002). Vegetation indices have been used extensively in vegetation monitoring, as they are correlated with various parameters that describe vegetation condition, such as green leaf area index (LAI), phenology, fraction of photosythetically active radiation absorbed by vegetation (fAPAR), canopy density, dryness, and the health of natural and managed vegetation (Asrar *et al.* 1984, Gao 1996, Gitas *et al.* 2004, Silleos *et al.* 2002, Zhang *et al.* 2003). Among the numerous vegetation indices available, the Normalized Difference Vegetation Index – NDVI (Kriegler *et al.* 1969, Rouse *et al.* 1973) is widely used for monitoring vegetation condition (Baret and Guyot 1991, Huete *et al.* 1985) due to its advantages, although certain drawbacks have been reported (Huete *et al.* 2002). Since the methods developed for monitoring vegetation condition using vegetation indices (Moulin *et al.* 1997, White *et al.* 1997) are difficult to apply on regional or nationwide scales due to frequent cloud cover and variable viewing angles (Zhang *et al.* 2003), multi-temporal image composites have been proposed for large-scale operations (Qi *et al.* 1993, Sousa *et al.* 2003, Chuvieco *et al.* 2005, Ferreira and Huete 2004, Maselli 2004).

The problems reported when monitoring vegetation condition on these scales are the frequent appearance of clouds, the low viewing angles and the poor geometric registration (Huete *et al.* 2002, van Leeuwen *et al.* 1999). When it comes to the operational monitoring of vegetation condition, the temporal frequency of observation becomes an important issue. The recent abundance of satellite images (daily or twice per day) may lead to an increased demand for storage and high processing abilities. The immediate answer would be to sample or aggregate the data using a certain temporal step (i.e. temporal resolution), which could be conceived as the temporal scale of the data. One of the problems with temporal scale is that data may carry different information when sampled at different temporal resolutions. Each level of scale has its own unique properties, and new properties emerge when data are sampled in a different step (Bian 1997). Under-sampling may not accurately describe the phenomenon under consideration, while over-sampling, would increase the cost of the project without additional benefit. Therefore, the selection of a correct temporal resolution is important to ensure that the desired phenomenon is monitored and the procedure is cost effective (Cao and Lam 1997, Goodchild and Quattrochi 1997).

In all of the aforementioned vegetation monitoring studies, no particular consideration was taken with regard to the optimal time step for monitoring vegetation, apart from the impact of variable temporal frequency in a change detection study (Lunetta *et al.* 2004), and the effects of temporal scale on the Amazon forest fragmentation assessment (Ferraz *et al.* 2006). Satellite image distribution centres provide NDVI multi-temporal composite products at several temporal resolutions: Terra / MODIS at 16 days and montly (LP-DAAC 2005), NOAA / AVHRR at 10 days and monthly (EOSDIS 2002), and SPOT / VEGETATION at 10 days (VEGETATION 2004). Their selection of temporal resolution is a trade-off between cloud screening and monitoring of dynamic vegetation changes, which is considered on a global scale (Huete *et al.*

1999). However, based on the above, it seems that local variability, period of observation, and monitored parameter could influence the selection of temporal resolution.

Monitoring vegetation on a nationwide scale can be performed using wide coverage satellite images (NOAA AVHRR, Terra/Aqua MODIS, SPOT VEGETATION). Among the available satellite sensors, MODIS provides the highest spatial and spectral resolution and is more sensitive to vegetation condition (Huete *et al.* 2002, van Leeuwen *et al.* 1999). The aim of this work was to estimate the optimum temporal resolution for monitoring vegetation on a nationwide scale using 250m MODIS/Terra daily images and composites. A preliminary estimation was carried out for the Mediterranean environment of Greece, during the dry season, using NDVI as a parameter that describes general vegetation condition and phenology. Specific objectives were:

(i) to investigate the optimum temporal resolution for monitoring vegetation condition using time-series analysis of NDVI dataset;

(ii) to investigate whether this temporal resolution differs between the two major vegetation categories, namely natural and managed vegetation;

(iii) to assess the quality of multi-temporal NDVI composites, following the proposed optimum temporal resolution.

## 2. Description of the study area

The study area is the whole of Greece, and in this work it is studied in three levels of land cover, which provide eight cases:

- the whole study area: Greece (a),
- the two main vegetation categories: Managed (b) and Natural (c), and
- the five test sites: Giannitsa (d), Kilkis (e), Malakasa (f), Taxiarhis (g), and Pertouli (h).

(a) The whole study area (Greece), covers an area of 131 000 km2. The area consists of the mainland, and numerous large and small islands. It is located in the Mediterranean climatic zone, with temperatures ranging from below 0oC in the winter to 35oC in the summer. The mean annual precipitation varies throughout the country, ranging from 400 to 1800 mm/year, corresponding to the strongly undulating terrain. The wet months are March, April and November, while July and August are very dry.

Vegetation cover of the area is typically Mediterranean and, can be classified into two major categories: natural (59%) and managed (41%), based on CORINE Land Cover 2000 of Greece (MINENV 2004). Since the two main vegetation categories of the study area are different in their phenological cycles, it was decided to study them separately and provide results for each main vegetation category. Two geographical zones were therefore defined, managed and natural vegetation, using a generalized CORINE Land Cover map. The map's scale (1:100 000) was adequate for a nationwide study, and its production date (2000) was not expected to create any problems at this level of generalization.

(b) The phenological cycle of managed agricultural vegetation is repeated on an annual basis. Development phases include seeding, growth, maturity and harvesting, which can largely be controlled by modern agriculture. Factors such as current meteorological conditions, irrigation status and availability of equipment influence the timing. Generally, there is one growing season from early spring to early autumn.

(c) Natural vegetation consists of coniferous and deciduous forest, shrubs and pastures. The phenological cycle of natural vegetation is relatively stable throughout the year, except in the case of extreme weather conditions. Generally, the various types of vegetation leaf-out, grow to maturity and senesce at approximately the same time each year. The most notable changes occur after the dormant phase of winter, when rapid growth takes place in the spring, followed by senescence in late summer or early autumn.

To study vegetation dynamics in more detail, and provide specific results for typical vegetation types within the two major vegetation categories, five test sites were selected. These comprised homogeneous areas of 15 $km^2$ (240 MODIS pixels each) of various typical natural and managed vegetation types. Spatial homogeneity within each test site was high at the nationwide scale level, and was tested using the standard Shannon's Diversity Index - SHDI (McGarigal and Marks 1994) estimated from CORINE Land Cover data. SHDI is based on the information theory of Shannon and Weaver (1949), and is sensitive to richness of land cover types within each test site. It ranges from 0 (high homogeneity) to infinite (high heterogeneity), but considering the size of the test sites and the minimum mapping unit of CORINE Land Cover (0.25 $km^2$), its maximum value could not exceed 3.39. A location map is provided in figure 1. Below follows a short description of each test site in terms of its landscape, climate, water, vegetation regime and spatial diversity:

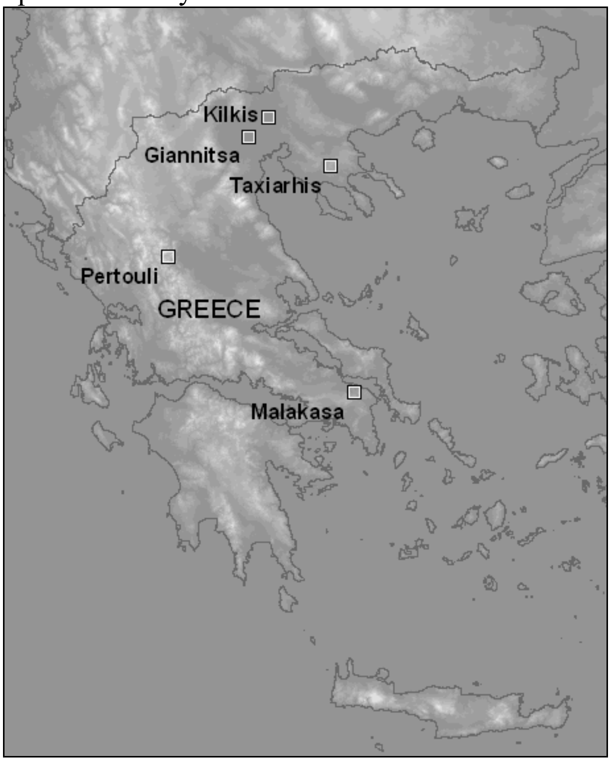


Figure 1. Location of test sites. Background: elevation map, in which light grey indicates higher elevation.

(d) The Giannitsa test site is located at N40°42’12’’, E22°27’50’’, with mean elevation of 12m. Mean annual precipitation is 800mm, and summers are warm and dry. It is an intensively agricultural area, with a developed irrigation and drainage network system. The terrain is flat, and vegetation cover mainly consists of annual crops (maize, cotton, alfalfa) and, to a minor extent, orchards. The phenological stages of the dominant crops include leaf-out in late spring, full growth in summer, and maturity in early autumn. SHDI is equal to 0.02, revealing very high homogeneity.

(e) The Kilkis test site is located at N40°43’34’’, E22°35’24’’, with a mean elevation of 65m. Mean annual precipitation is 450mm, which is distributed during the winter and spring months. Winters are cold and summers are warm and dry. The landscape is very mildly undulating with gentle slopes. Vegetation cover is agricultural, apart from narrow streams with natural vegetation. A very sparse groundwater irrigation activity has been developed in the area, therefore the main crops comprise winter cereals. These are sown and leaf-out in winter, grow in spring, and reach maturity early summer. SHDI is equal to 0, revealing the absolute homogeneity of a single land cover class.

(f) The Malakasa test site is located at N38°12’52’’, E23°43’30’’, with a mean elevation of 290m. Mean annual precipitation is 450m, distributed unevenly during the autumn and winter months. The summers are warm and dry, and winters are mild. Landscape is mildly undulating, and the numerous streams are of seasonal flow. Vegetation cover is mixed forest with shrubs. Due to the dry conditions, leaf-out and growth of vegetation occurs early in spring. SHDI is equal to 0.54, revealing high homogeneity.

(g) The Taxiarhis test site is located at N40°26'01'', E23°30'06'', with a mean elevation of 850m. Mean annual precipitation is 746mm, unevenly distributed during November-December and May-June. The landscape is mountainous and forms seasonal streams, and no sources of surface water exist during the warm and dry summers. Vegetation cover is mainly mixed forest, with deciduous and coniferous species and small patches of agricultural vegetation. Although vegetation characteristics are diverse, leaf-out and growth occur in spring and early summer. SHDI is equal to 0.50, revealing high homogeneity.

(h) The Pertouli test site is located at N39°31'45'', E21°29'58'', with a mean elevation of 1100m. Mean annual precipitation is 1700mm, but during the leaf-out and growing season (May-September) it is only 300 mm. The landscape is mountainous with numerous small basins that form small streams of seasonal flow and some springs of constant flow. Vegetation cover is coniferous forest. SHDI is equal to 0.39, revealing high homogeneity.

## 3. Materials and methods

### *3.1 Image acquisition and pre-processing*

A series of MODIS/Terra satellite images was acquired from the Distributed Active Archive Centre of NASA's Earth Observing System Data Gateway (http://edcimswww.cr.usgs.gov/pub/imswelcome/). The data series covered the period from May 1st, 2003 to October 31st, 2003 on a daily basis (Julian days 121 to 304) in order to depict the major changes in vegetation condition of natural and agricultural vegetation in the study area. It should be noted that this is the time period when dry conditions dominate in the semi-arid Mediterranean environment of the study area, and is the season of main importance for monitoring both natural and managed vegetation condition.

The data product requested was MODIS/Terra Surface Reflectance Daily L2G Global 250m SIN Grid (product code MOD09GQK). This product provides the surface reflectance recorded at bands 1 and 2 (red and near-infrared, centred at 648 nm and 858 nm, respectively), as it would have been measured at ground level if there had been no atmospheric scattering or absorption. A correction scheme was applied by the MODIS processing team on a pixel basis in order to reduce the effects of atmospheric gases, aerosols and thin cirrus clouds, as well as adjacency effects caused by variation of land cover, bi-directional reflectance and atmosphere coupling effects (Vermote and Vermeulen 1999). This product was selected in preference to the others, as atmospheric correction was considered essential for time-series analysis (Song *et al.* 2001). In addition, the quality control flags held in the same product were utilized to mask out low quality pixels, or discard images of unacceptable quality, as necessary. The quality flags contain information about the success of correction algorithms for atmospheric influence and adjacency effects, coded in a 16bit pattern.

The products were received in tiles projected in the Sinusoidal coordinate system, and three tiles were mosaicked in order to cover the study area. The projection system was converted to the Hellenic Geodetic Reference System using a geocentric transformation method. The geographic error inserted by the transformation was negligible in relation to the coarse resolution (250m pixel size) of the products used.

### *3.2 Preparation of NDVI time-series*

NDVI, which is one of the standard indices used to describe vegetation condition (Huete *et al.* 2002), was employed in this study. The surface reflectance on bands 1 and 2 were used to calculate NDVI:

$$NDVI = (\rho_{NIR} - \rho_{red}) / (\rho_{NIR} + \rho_{red}) \quad \text{(Eq. 1)}$$

where $\rho_{NIR}$ is the surface reflectance calculated for the second band (near infrared) and $\rho_{red}$ for the first band (red), respectively. The resulting NDVI raster images were kept in the original decimal number format ranging from –1 to +1 in order to facilitate interpretation of the vegetation index, although the large digital files of this format would hinder further processing.

The frequent and irregular appearance of clouds was the greatest problem encountered in this attempt to create a time-series using passive satellite images. Extensive cloud cover can mask vegetated areas, while small clouds can distort the recorded vegetation reflectance. Accurate delineation and removal of the clouds on a per image basis was beyond the scope of this study. Areas covered with rock, infrastructures, water, snow, ice and clouds have a significantly lower NDVI value compared to vegetated areas (Hoffer 1978). A list of threshold values that can be used for differentiating vegetation phenologies has already been reported (White *et al.* 1997). In this case, a value of 0.2 was used to mask out non-vegetated areas, and consequently to exclude them from further analysis. To identify this threshold value, a random set of 150 points was sampled on MODIS NDVI images to include vegetated and non-vegetated areas (rock, bare land, settlements, inland water, cloud, cloud shadow and snow), and was plotted on a graph. The threshold was located between the distinctive curves of vegetated and non-vegetated pixels.

Daily values of NDVI were calculated by simple averaging all pixel values in the respective area (study area, vegetation zone, and test site) of the NDVI raster images, since the goal of this study was not to investigate within site variation or spatial autocorrelation. The respective areas were large enough, in comparison with the pixel size used, and so a more sophisticated technique (Maselli 2004) for extraction of NDVI values was not necessary. These values were recorded on a spreadsheet and were presented in graphs. Each plotted point in the graph was the average of the daily NDVI raster image in the respective area (study area, vegetation zone, or test site). A large amount of variation among the observed NDVI values was evident. Sources of noise could have been residual cloud and aerosol contamination, other atmospheric influences not accounted for during atmospheric correction of the MODIS product, or saturation of the vegetation index (Huete *et al.* 2002, Roy *et al.* 2002, van Leeuwen *et al.* 1999). To test the hypothesis if viewing geometry was a significant source of noise, solar and sensor angles were collected for 30 randomly selected days in the study period, from the MODIS/Terra Geolocation Angles Daily L2G Global 1km SIN Grid Day (MODMGGAD) product. Correlation coefficients of observed NDVI values with solar and sensor angles were very low ($r = -0.014$ and $r = -0.028$, respectively, $n = 30$), therefore there is insufficient evidence to conclude that the observed noise was related to viewing geometry.

Smoothing is a frequently used technique for separating the long-term variability (trend) from the short-term variability (noise) of time series. The basic assumption behind smoothing models is that the time series is locally stationary with a slowly varying mean, which is true for NDVI (White *et al.* 1997). Cubic spline smoothing was employed to remove noise and reveal the trend component of the NDVI time series. The cubic spline method used a set of third-degree polynomials spliced together such that the resulting curve is continuous and smooth at the splices (knot points). The estimation was done by minimizing the objective function, which is a combination of the sum of squares error and a penalty for curvature integrated over the curve extent (Eubank 1988, Reinsch 1967). The rationale for selecting cubic spline was that a flexible model could better describe any significant variation in vegetation condition.

Lambda (λ) was the parameter in spline smoothing that controls the trade-off between smoothness of the estimate and fidelity to the data, and was selected by examination of the data using empirical methods. According to Gardner (1985) the residuals of an optimum smoothed line should not be autocorrelated, because the line should be able to describe all the information from the original time series. The Durbin-Watson statistic (Durbin and Watson 1971) was used to test for serial autocorrelation, which is approximated for moderate sample sizes as (equation 2):

$$DW \approx 2(1 - r_m) \qquad \text{(Eq. 2)}$$

where $r_m$ is the lag1 residual autocorrelation (White 1992).

Therefore, the criterion for lambda selection was the Durbin-Watson test, which was used to verify that the smoothed line described sufficiently the information from the original time-series, and thus would not influence the subsequent analyses. After testing a series of lambdas, the optimum value for smoothing the time series was selected for the study area, vegetation categories, and test sites, based on the criterion.

### *3.3 Analysis of NDVI time-series*

Analysis of the time series was first performed visually. After removing discontinuities and outliers, the mean NDVI series was plotted against time in order to identify any notable trends. Visual analysis was initially performed for the study area.

The theoretical background of spatial autocorrelation has been outlined for remote sensing applications (Curran and Atkinson 1998, Jupp *et al.* 1988). Study of spatial autocorrelation and other forms of geostatistics have been used to identify the optimum ground sampling for field surveys (Atkinson 1991), the optimum image spatial resolution (Marceau *et al.* 1994), and the appropriate filter size (N'Kanza and Naizot 1993). Similar to one-dimensional spatial autocorrelation, time-series analysis uses techniques to study the dependency of observations in time (Wooldridge 2000).

Temporal autocorrelation has been used extensively in economic sciences to analyse time-series and identify their characteristics (Intriligator *et al.* 1996), and relatively less in forestry and ecological sciences (Gumpertz *et al.* 2000, Kohyama *et al.* 2005). The autocorrelation function $r_m$ of a series of continuous data at lag $m$ is the relation between $x_i$ and $x_{i+m}$ and can be calculated using equation (3):

$$r_m = \frac{\sum_{i=1}^{n-m} (x_i - \bar{x})(x_{i+m} - \bar{x})}{\sum_{i=1}^{n} (x_i - \bar{x})^2} \qquad \text{(Eq. 3)}$$

for lags $m = 2,3, \ldots, n/4$, where $\bar{x}$ is the mean of $n$ observations.

The autocorrelation function of daily NDVI measurements was estimated using equation (3), and was graphically depicted in a correlogram, as a series of bars describing the correlation $r_m$ between all the pairs of NDVI measurements in the time-series with a given separation in time (lag). Using this technique, the correlation between NDVI measurements taken one, two or several days apart was examined. Ranges of two standard errors for each lag were marked on the correlogram, which is an indication of its reliability.

Generally, autocorrelation is high at small lags and decreases with lag increasing. In the study area, the evolution of vegetation at various phenological stages is relatively slow, except for certain processes (fire, frost, harvesting of fresh plants), therefore vegetation indices were expected to be correlated at small lags. At very large lags, on the other hand, significant changes of vegetation status should be observed, but certain processes in between could be omitted. Nevertheless, strong, and thus highly significant autocorrelations were of interest. The t-statistic was employed to check the level of significance of temporal autocorrelation, which is a robust criterion under conditions of model uncertainty (Perrier and Wilding 1986).

In this study, the optimum temporal resolution for monitoring vegetation was defined as the smallest lag at which temporal autocorrelation was not highly significant, tested with the t-statistic. Thus, when monitoring vegetation at the optimum temporal resolution, one can be certain to detect significant changes and, at the same time, avoid over-sampling.

### *3.4 Analysis at various vegetation categories*

Visual and temporal autocorrelation analyses were initially performed on the time series of the whole study area. In order to explore the differences between major vegetation categories, analyses were repeated separately for each major category. Visual analysis was performed for the mean NDVI values of the vegetation zones and the five test sites, which were plotted on a single graph to facilitate comparison. Similarly, temporal autocorrelation analysis was performed separately on the time series of the two vegetation zones, and the five test sites, in order to explore whether the optimum temporal resolution varies between vegetation types.

During preparation of the time-series, the only parameter that was subjectively defined and that could influence the final result was lambda of the spline smoothing. In order to check the sensitivity of the result to this parameter, sensitivity analysis of the optimum time step with lambda was also performed (equation 4).

$$SI = \frac{r_t}{r_\lambda} \cdot \frac{m_\lambda}{m_t} \qquad \text{(Eq. 4)}$$

where SI is the sensitivity index (low values indicate low sensitivity of result on the examined parameter), $r_t$ and $m_t$ is the range and mean of values for the proposed optimum temporal resolution, respectively, and $r_\lambda$ and $m_\lambda$ is the range and mean of values for lambda, respectively. Sensitivity analysis measures the impact on the outcomes of changing an input parameter about which there is uncertainty (Marshall 1999). The low values of sensitivity index (table 1) proved that the selection of lambda during the smoothing process of the time-series could not have influenced identification of the optimum temporal resolution.

### *3.5 Multi-temporal NDVI compositing*

One of the most frequently used means for operational vegetation monitoring is multi-temporal image composites, as opposed to images sampled in the time dimension, because of the numerous advantages (van Leeuwen *et al.* 1999, White *et al.* 1997). After selection of the optimum temporal resolution for monitoring vegetation, NDVI image composites were created. The standard Maximum Value Composite (MVC) technique was selected among others (Cihlar *et al.* 1994) because its simplicity was expected to facilitate interpretation of the results. The NDVI composites were created using the same dataset over the study area, and they differed only in the number of image days used for each, i.e. they had different temporal compositing periods. These compositing periods followed closely the results of the time series analysis, although a few additional periods were created for reasons of comparison.

Several tests were performed to assess the quality of the composites, and thus their effectiveness in minimizing errors and justifying their advantages in operational monitoring. The tests performed were modifications of the tests reported in Chuvieco *et al.* (2005), which were originally used to assess the quality of composites in different techniques for burned area mapping, using a set of criteria. The modified criteria used in this study to assess the quality of various time-step composites were:

1. Variation from daily NDVI values. This test measured the difference between multi-temporal composites and the daily NDVI images that corresponded to the same time period. The best composite should display only small differences in comparison to daily NDVI images.
2. Presence of artifacts. For each composite, the pixels that retained abnormal NDVI values were counted. Test sites had been selected to have a homogeneous land cover, therefore pixels with NDVI value lower than or equal to the threshold of 0.2 represented reception problems: clouds, cloud shadows, missing data, etc. The best composite should have retained the least number of artifacts.
3. Spatial coherency. This test examined the mosaic effect of the composite image, which could be affected: (i) either by the blocking effect inserted to composites by selecting single

pixels from various dates, acquired under different conditions, or (ii) by the smoothing effect of MVC, which tends to retain only maximum values. Variance calculated in the test sites was used as a measure of spatial coherency. The best composite should have a similar texture to that of a single date image.

Direct quantitative comparison was not possible between the NDVI composites of this study, as they originated from different time periods. Therefore, results were derived for qualitative comparison only, and also to facilitate discussion.

A 32-day period (Julian days 145-176) with varying atmospheric and vegetation conditions was selected to carry out the quality tests of the NDVI composites in the five test sites. This period included four days of continuous cloud cover for three test sites (Julian days 145-148), and some other isolated cloud cover events. Three compositing periods were tested to check their quality. These were a 4-day, an 8-day, and a 16-day composite.

The following flowchart (figure 2) describes the outline of the methodology.

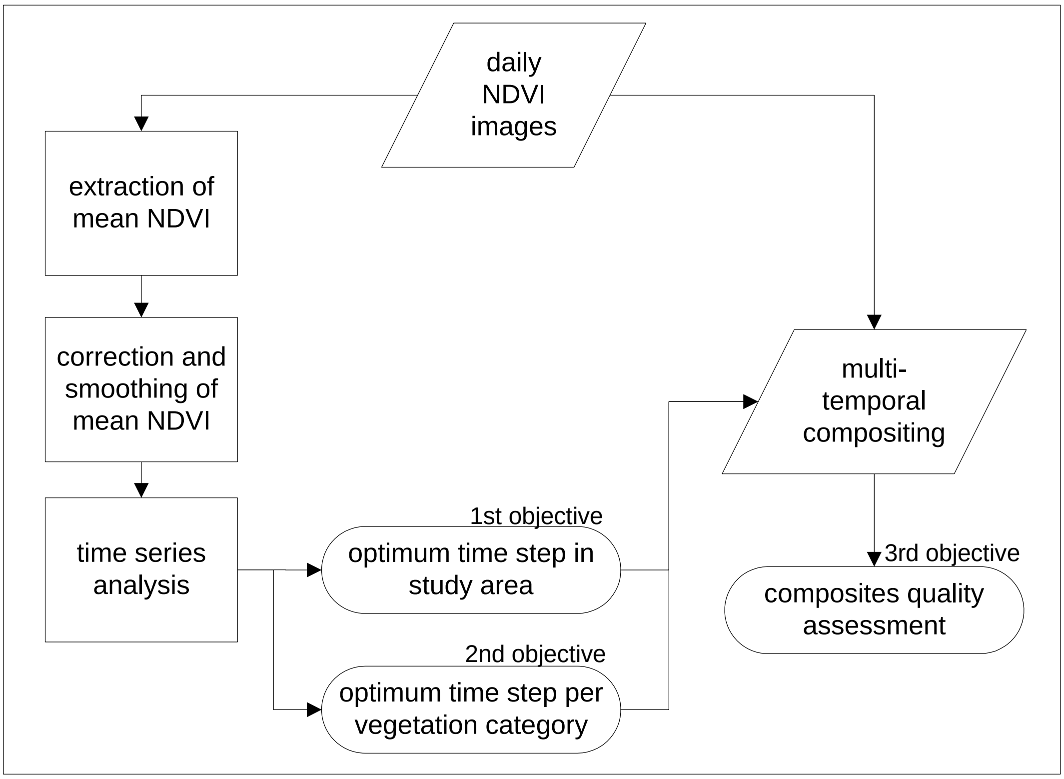


Figure 2. Overview of data analysis.

## 4. Results and discussion

### *4.1 Optimum temporal resolution in study area*

The smoothed NDVI values for the study area, vegetation zones, and test sites are presented in figure 3. The selected values of lambda for the smoothing function at the equivalent areas are listed in table 1. The main trend observed from visual analysis of the mean NDVI for the study area was a steady drop throughout the examined period. By May, most of the natural and non-irrigated managed vegetation had reached maturity, and the progressively drier weather had led to a gradual senesce. The slight increase during June (Julian day 150 to 175) could be attributed to the increasing vegetation cover of irrigated agriculture, and the late development of natural vegetation at high altitudes. However, the expected temporal variability was not evident, as vegetation condition in the study area was represented by a single averaged NDVI value.

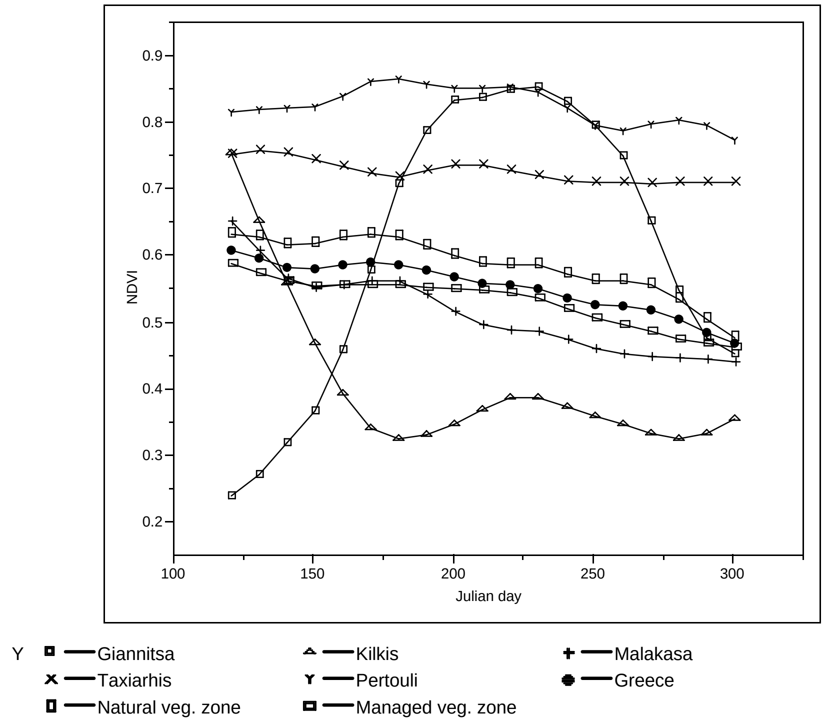


Figure 3. NDVI series recorded in study area, vegetation zones, and test sites, after removing noise.

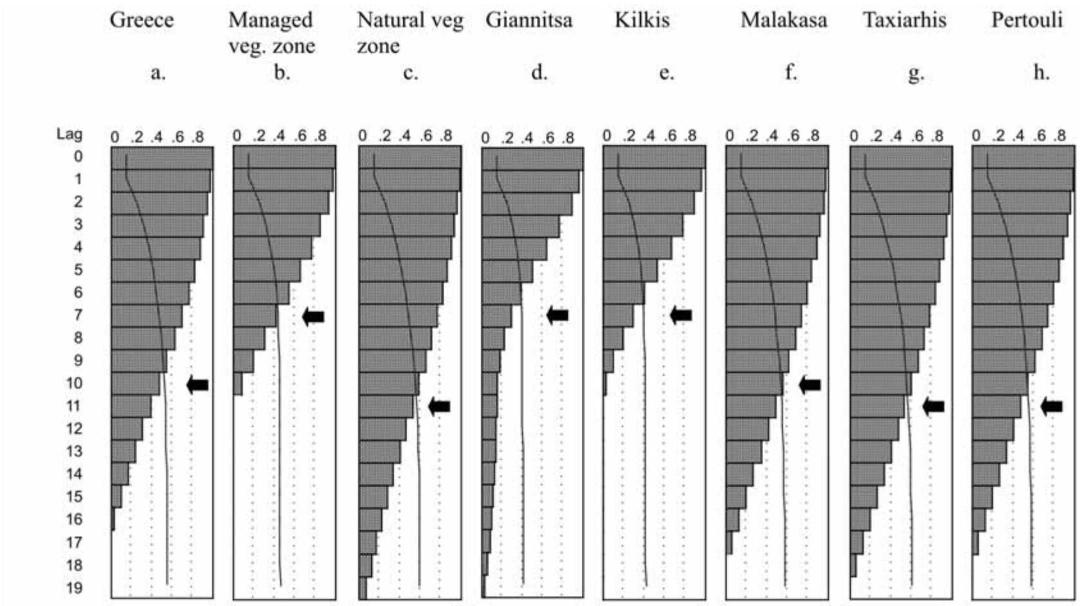


Figure 4. Autocorrelation function plots for determining optimum temporal resolution for monitoring vegetation in the study area (a), managed (b) and natural (c) vegetation zones, and the five test sites (d to h). Bars indicate autocorrelation. Black arrows indicate the smaller lag with non-highly significant autocorrelation. Curves denote the range of two standard errors for each lag.

The computed autocorrelation function plot for the study area is displayed in figure 4a. The smallest lag with non-highly significant autocorrelation is marked with a black arrow (10 days). This is the proposed optimum temporal resolution for monitoring vegetation using NDVI, according to the objective function defined in this study, and is an averaged result for natural and managed vegetation in the study area.

### *4.2 Differences at various vegetation categories*

Results from visual analysis of temporal plots of mean NDVI for the major vegetation zones and five test sites provided a number of notable trends (figure 3). The main characteristics and trends observed were:

- For the natural vegetation zone, a peak of NDVI was observed in May or earlier. This coincided with the period of maximum accumulation of photosynthetically active biomass. After May, there was a clear negative trend.
- NDVI of the managed vegetation zone was relatively steady until August (Julian day 225), after which a steadily negative trend was observed. This could possibly be attributed to the combined effect of irrigated and non-irrigated agriculture, both of which display a diverse behaviour.
- More specifically, for the natural vegetation test sites, the Malakasa test site displayed a steadily negative trend, due to the unfavourable hydric conditions beginning in the spring and prevailing through the summer. The Pertouli and Taxiarhis test sites, however, demonstrated a stable vegetation condition, with a few abrupt drops towards the end of summer (after Julian day 200), and a slight delay of leaf-out in Pertouli because of the higher altitude. Clearly, the type of vegetation and the weather conditions favoured a steady NDVI response over the examined period.
- Irrigated agricultural vegetation (Giannitsa test site) revealed a relatively late peak (Julian day 200 to 230). Cash crops in the study area had a distinct delay in their phenological stages, in order to take advantage of maximum incoming solar radiation of summer months.
- Non-irrigated agricultural vegetation (Kilkis test site) had a maximum in late spring (Julian day 121), similar to natural vegetation. Its drastic drop could be attributed to the uniform timing of maturity and harvesting in early summer (from Julian day 121 to 170). The slight increase in August (Julian day 225) might have been due to the development of sparse weed, after harvesting of the crops.

In general terms, the curves referring to the major vegetation zones display certain similarities, which can be attributed to within zone variability. Indeed, differences are amplified in the test sites' curves.

Computed autocorrelation function plots for major vegetation zones and the test sites are displayed in figure 4 (b to h). The proposed optimum temporal resolution for monitoring vegetation using NDVI is summarised in table 1.

Table 1. Results of time-series analysis and sensitivity analysis in the study area (a), managed (b) and natural (c) vegetation zones, and the five test sites (d to h).

| Statistic | Greece<br>a. | Managed veg. zone<br>b. | Natural veg. zone<br>c. | Giannitsa<br>d. | Kilkis<br>e. | Malakasa<br>f. | Taxiarhis<br>g. | Pertouli<br>h. |
|---|---|---|---|---|---|---|---|---|
| Selected value of lambda for smoothing function | 10 000 | 10 000 | 10 000 | 20 000 | 20 000 | 50 000 | 10 000 | 50 000 |
| Sensitivity index of | 0.326 | 0.330 | 0.245 | 0.390 | 0.357 | 0.193 | 0.217 | 0.198 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| lambda for optimum temporal resolution (no units) | | | | | | | | |
| Proposed optimum temporal resolution (days) | 10 | 7 | 11 | 7 | 7 | 10 | 11 | 11 |

The proposed optimum temporal resolution ranged from 7 to 11 days. This is a relatively large range for a country the size of Greece, and is probably due to the varying climatic conditions (Loukas *et al.* 2001). Natural vegetation sites displayed a relatively larger optimum time-step (10-11 days). Clearly, natural vegetation phenology is characterized by a smooth temporal transition under normal natural conditions, when drastic changes such as infestations, fires or clear cuts do not occur. Plants have evolved to adapt to local natural conditions, and therefore only small changes were evident in the time series, requiring a larger period for monitoring. On the other hand, managed vegetation displayed a smaller optimum time-step (7 days). Farmers' intervention with irrigation, weeding, spraying with insecticides, etc., had helped the plants withstand environmental conditions. Under these artificial conditions, plants grew, matured and senesced uniformly, displaying a rapid increase and decrease, and therefore requiring a shorter monitoring period.

Changing the level of scale to the zones, the proposed optimum time-steps were 11 days for the natural vegetation zone and 7 days for the managed vegetation zone. These results were consistent with the specific test sites, indicating that there is no spatial scale effect (Cao and Lam 1997).

### *4.3 Quality assessment of multiple temporal resolution composites*

The results of the quality tests, which were employed to assess the quality of the composites, and thus their effectiveness in operational monitoring, are displayed in table 2. The results from three tests are presented separately by compositing period and by test site.

Table 2. Quality check of composites at various temporal resolutions (2a: 4-day composite, 2b: 8-day composite, and 2c: 16-day composite). Units of tests: Variation from daily values (no units), Presence of artifacts (number of pixels), and Spatial coherency (no units).

| Test | Giannitsa (clear) | Kilkis (cloudy 4/32 days) | Malakasa (clear) | Taxiarhis (cloudy 8/32 days) | Pertouli (cloudy 10/32 days) |
|---|---|---|---|---|---|
| 2a. 4-day composite | | | | | |
| Variation from daily values | 0.078 | 0.096 | 0.117 | 0.013 | -0.001 |
| Presence of artifacts | 0 | 64 | 0 | 125 | 127 |
| Spatial coherency | 0.088 | 0.058 | 0.101 | 0.040 | 0.016 |
| 2b. 8-day composite | | | | | |
| Variations from daily values | 0.146 | 0.151 | 0.154 | 0.088 | 0.001 |
| Presence of artifacts | 0 | 0 | 0 | 12 | 26 |
| Spatial coherency | 0.068 | 0.061 | 0.064 | 0.039 | 0.030 |
| 2c. 16-day composite | | | | | |
| Variations from daily values | 0.221 | 0.256 | 0.177 | 0.195 | 0.128 |
| Presence of artifacts | 0 | 0 | 0 | 0 | 0 |
| Spatial coherency | 0.064 | 0.135 | 0.061 | 0.065 | 0.072 |

Regarding variation from daily values, as the compositing period increased, average differences from daily values increased. This is an indication that large period composites cannot follow frequent vegetation condition changes. Some differences are large (maximum: 0.256), which could have been magnified by the nature of MVC algorithm.

As expected, artifacts decreased with an increase in the compositing period. On test sites with cloud events, a 4-day composite was unable to account for them, an 8-day composite had accounted for most of them, and a 16-day composite had completely removed the cloud and cloud shadow effects.

Spatial coherency values were already low, due to high homogeneity in the selected test sites. As compositing period increased, spatial coherency: (i) increased on test sites with cloud events, due to the selection of diverse pixels from a wider range of days to form the composite, and (ii) decreased on test sites without cloud events because of the smoothing effect of MVC, which introduced a bias towards higher values.

The trends observed in these qualitative tests were consistent throughout the examined composites (4, 8, and 16 days). Therefore, by selecting a compositing period similar to the optimum temporal resolution (7, 10, and 11 days) for monitoring vegetation condition, NDVI values were only slightly distorted, most artifacts were removed, and spatial homogeneity was preserved. Considering these, the proposed compositing period has provided products that can be used on an operational vegetation monitoring project.

## 5. Conclusions

This study took into account the nature of actual satellite observations to explore the issue of temporal sampling for monitoring vegetation condition, as it is described with vegetation indices. Daily MODIS data and multi-temporal composites were successfully used to estimate the optimum temporal resolution for operational vegetation monitoring in Greece, during the dry season. Temporal autocorrelation analysis was used, and its level of significance was the adopted objective function criterion.

Taking into account the whole study area, the 10-day period was the proposed optimum time step. This result refers to monitoring the combined vegetation of the study area, including both managed and natural vegetation categories.

The estimated optimum temporal resolution varied according to vegetation category. The result for managed vegetation was 7 days, and for natural vegetation 11 days. Therefore, monitoring the condition of managed vegetation requires a more frequent temporal resolution than that for natural vegetation. This difference can be attributed to the slow phenological cycle of natural vegetation, and the dependency of managed vegetation on farmers' practices.

Finally, an assessment of the quality of multi-temporal composites revealed that compositing at the proposed optimum temporal resolution could derive products that are useful for operational vegetation monitoring.

Agencies involved in nationwide vegetation monitoring in the study area, namely the Civil Protection Agency, the Organization for Farmers' Insurance, and the Ministry of Agricultural Development and Foods, might use the findings of this study to optimise the efficiency of their monitoring schemes. In addition, the conclusions drawn from this work could be taken into account during the design process of additional MODIS products.

Conclusions from this study are limited to the extents of a Mediterranean country, the duration of the dry season, and a vegetation index. Nevertheless, the outlined methodology should be implemented in larger areas and multiple annual periods. It is proposed that further work focus on investigation of different variables that characterize vegetation status (e.g. Leaf Area Index, Fractional Vegetation Cover) at different spatial resolutions to monitor larger countries or continents. Also, connection with field observations of vegetation status and phenology could provide the basis for in-situ validation.

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