Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
Remote Sensing of Environment 89 (2004) 423–433
Remote Sensing of Environment
www.elsevier.com/locate/rse

Monitoring forest conditions in a protected Mediterranean coastal area by the analysis of multiyear NDVI data

Fabio Maselli

IBIMET-CNR, Institute of Bio-Meteorology, Piazzale delle Cascine 18, 50144, Florence, Italy

Received 26 May 2003; received in revised form 10 October 2003; accepted 14 October 2003

Abstract

The operational utilization of remote sensing techniques for monitoring terrestrial ecosystems is often constrained by problems of under-sampling in space and time, particularly in heterogeneous and unstable Mediterranean environments. The current work deals with the use of the NOAA-AVHRR and Landsat-TM/ETM+ images to produce long-term NDVI data series characterising coniferous and broadleaved forests in a protected coastal area in Tuscany (Central Italy). Two methods to extract NDVI values of relatively small vegetated areas from NOAA-AVHRR data were first evaluated by comparison to estimates from higher resolution Landsat-TM/ETM + images. The optimal method was then applied to multitemporal AVHRR data series to derive 10-day NDVI profiles of coniferous and broadleaved forests over a 15-year period (1986–2000). Trend analyses performed on these data series showed that notable NDVI decreases occurred during the study period, particularly for the coniferous forest in summer and early fall. Further analysis carried out on local meteorological measurements led to identify the likely causes of these negative trends in contemporaneous winter rainfall decreases which were significantly correlated with the found NDVI variations.

Keywords: AVHRR; TM/ETM+; NDVI; Coniferous and broadleaved forests; Rainfall

1. Introduction

Forest ecosystems are an essential economic and environmental resource which is widely spread in most regions of the world. Unfortunately, both in developed and developing countries, many forests are presently threatened by the expansion of agricultural, urban, and industrial land or by degradation phenomena caused indirectly by human activities (Waring & Running, 1998). Climate changes in particular are an important cause of possible variations in the conditions of forests whose environmental equilibrium is fragile and vulnerable to perturbations. This is the case of most coastal Mediterranean ecosystems, for which summer water availability is usually the major limiting factor (Bolle, 1998; Lacaze et al., 1996; Odum, 1973). These ecosystems are therefore expected to be sensitive to the climate changes which are presently affecting the Mediterranean region (Palutikof, Goodess, & Guo, 1994). More specifically, rainfall decreases recently occurred in Italy (Brunetti, Maugeri, & Nanni, 2000; Buffoni et al., 2003) and might lead to negative evolutions of coastal forests which should be immediately detected in order to prompt appropriate remedies.

Among modern methods to monitor terrestrial ecosystems, remote sensing is of primary importance thanks to its capability of providing synoptic information over wide areas with high acquisition frequency (Richards, 1993). Traditionally, vegetation monitoring by remotely sensed data has been carried out using vegetation indices, which are mathematical transformations designed to assess the spectral contribution of green plants to multispectral observations. The potentials and limits of different vegetation indices have been extensively discussed in the literature (see for instance Bannari, Morin, Bonn, & Huete, 1995; Baret & Guyot, 1991). Vegetation indices are mainly derived from reflectance data from discrete red (R) and near-infrared (NIR) bands. They operate by contrasting intense chlorophyll pigment absorption in the red against the high reflectance of leaf mesophyll in the near infrared. Such is the case of the well-known normalized difference vegetation index NDVI=[NIR − R]/[NIR + R] (Bannari et al., 1995), which is the most widely used index especially when analyzing data taken from satellite platforms. In practice, NDVI is indicative of plant photosynthetic activity and has been

E-mail address: maselli@ibimet.cnr.it (F. Maselli).

0034-4257/$ - see front matter © 2004 Elsevier Inc. All rights reserved.
doi:10.1016/j.rse.2003.10.020

found to be highly related to the green leaf area index (LAI) and the fraction of photosynthetically active radiation absorbed by vegetation (FAPAR) (Bannari et al., 1995; Baret & Guyot, 1991; Veroustraete, Sabbe, & Eerens, 2002).

Thanks to these properties, NDVI can be utilized as an indicator of possible vegetation stress, particularly due to water shortage (Kogan, 1990; Millington, Wllens, Settle, & Saull, 1994). This is the case whenever water availability is the main limiting factor for vegetation processes and therefore controls leaf pigment content and integrity (Myers, 1983). Actually, NDVI values of arid or semiarid areas, as well as those of Mediterranean areas during the dry summer season, have been demonstrated to be strongly dependent on plant water availability in preceding months. This is true not only for grassland, but also for brushland and forestland, as demonstrated by works conducted in Africa (Davenport & Nicholson, 1993), Asia (Millington et al., 1994), North America (Walsh, 1987), Europe (Cannizzaro, Maselli, Caroti, & Bottai, 2002), and on a global scale (Ichii, Kawabata, & Yamaguchi, 2002). In particular, inter-year NDVI variations of not artificially altered Mediterranean vegetation covers are mostly controlled by variations in previous plant water stress conditions during the arid season (Caroti et al., 1995; Cannizzaro et al., 2002). Consequently, NDVI data are expected to reflect possible long-term variations in Mediterranean forest conditions due to changes in water availability.

In spite of these good premises, the operational utilization of satellite data for monitoring vegetation stress is generally limited by problems of under-sampling in space and time (Foody & Curran, 1994). The high inter-year variability in vegetation development in fact makes the detection of relevant stress conditions only possible by using frequently acquired data (at least every week—10-day period). As is well known, such frequent data can be only taken by low or medium spatial resolution satellite sensors (Bolle, 1996). More particularly, the National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) images are the only satellite product suitable for long-term retrospective studies with a sampling frequency sufficient for following rapid changes in vegetation status. Archives are in fact available which contain 10-day temporal composites of AVHRR data starting from the beginning of 1980s (Townshend, 1994). On the other hand, the relatively low spatial resolution of these data (about 1.1 km) poses problems in correctly identifying surfaces of limited extent which are typical of heterogeneous and fragmented Mediterranean ecosystems. This has encouraged studies on possible methods for integrating data with different spatial resolutions, which have had various degrees of success (Maselli, Gilabert, & Conese, 1998; Maselli & Rembold, 2002; Richards, 1993). Most of these studies were aimed at merging the useful spatial and temporal features of data acquired by different sensors, such as Landsat Thematic Mapper (TM) and NOAA-AVHRR.

Building on these considerations, the current investigation was aimed at developing and applying two procedures to extract information related to different vegetation types from AVHRR NDVI images. In particular, forest and agricultural ecosystems were considered within a protected coastal area in Southern Tuscany (Central Italy) having typical Mediterranean climate. The accuracy of the extracted NDVI values was evaluated by comparison to estimates from higher resolution Landsat Thematic Mapper or Enhanced Thematic Mapper (ETM+) imagery. The optimal method to extract NDVI values from AVHRR data was then applied to create long-term data series (from 1986 to 2000) characterising local coniferous and broadleaved forests. These data series were subjected to trend analysis aimed at identifying significant NDVI variations, which were finally interpreted by comparison to local meteorological measurements of the same period.

To reach its objectives, the paper is organised into the following sections:

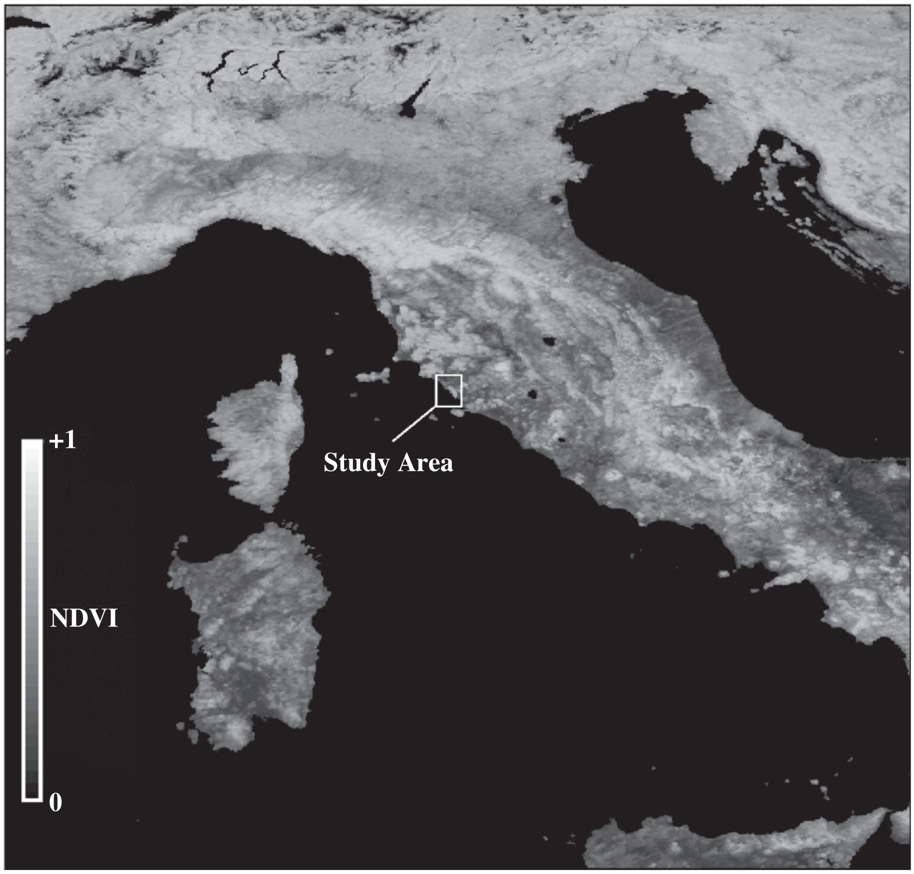
1. Description of the study area and data;
2. Processing of high- and low-resolution satellite images to extract and evaluate the NDVI data of different vegetation classes;
3. Application of trend analyses to the forest NDVI data;
4. Analysis of the possible causes of the forest NDVI variations found;
5. Discussion of the main results achieved and of their environmental implications;
6. Conclusions.

2. Study area and data

2.1. Study area

The Natural Park of Maremma covers a surface of about 5000 ha placed in the southern part of Tuscany, at around 42°39′N latitude, 11°02′E longitude (Fig. 1). The climate of the zone is typically Mediterranean, with moderate variations in temperature throughout the year and limited precipitation (500–600 mm) concentrated in the period from mid-autumn to early spring (Rapetti & Vittorini, 1995). According to the classification of Thornthwaite (1948), this climate can be described as mesothermic, between dry-subhumid and semiarid.

The park comprises the Ombrone delta, its coastal dunes, the southern Uccellina hills, and part of the surrounding plain (Fig. 2). The soils of the plain around the outlet of the Ombrone river are prevalently sandy, while those of the southern hills, which reach an elevation of about 400 m, are more structured (Innocenti & Pranzini, 1993). According to the vegetation map drawn by Arrigoni, Nardi, and Raffaelli (1985), schematized again in Fig. 2, the coastal plain is covered by three types of botanical associations. Two are herbaceous associations, while the third is represented by pine wood, (*Pinus pinea* L. and *Pinus pinaster* Ait.), described in the map as evergeen scrubland. This pine wood



has artificial origins, as it was planted at the beginning of the 19th century for coastal reforestation, but it adapted well to this kind of environment and developed for more than 150 years. Still, according to the same map, the southern hills are almost completely covered by a mixed broadleaved forest mostly composed of various oak types (Arrigoni et al., 1985). This is an ecosystem in natural equilibrium with the environment which is representative of Mediterranean semi-deciduous woodland. The rest of the plain around the Ombrone delta and the Uccellina hills is covered by pastures and fields cultivated with various winter and summer crops.

2.2. Meteorological data

Daily meteorological data were derived from a station of the Italian National Hydrological Service situated near the Ombrone delta within the Natural Park of Maremma. The meteorological data set consisted of complete series of daily temperatures (minimum and maximum) and precipitation from 1986 to 2000.

2.3. Remotely sensed data

2.3.1. High-resolution data

Images acquired by the Landsat 5 and 7 satellites were used as high-resolution data. As is well known, both these sensors acquire optical radiation in six spectral bands with a spatial resolution of 30×30 m and a revisiting period of 16 days. Nine Landsat 5 TM images taken in different seasons over an 11-year period (1988–1998) were considered, together with five Landsat 7 ETM+ images acquired in 2000. The complete list of the TM and ETM+ images utilized is reported in Table 1, with the indication of the relevant acquisition dates. As can be seen, most of the images were taken during the summer dry period (July–August), but some of them were also descriptive of vegetation status in spring (March–June) and early fall (September). All these images were cloud-free and practically unaffected by other atmospheric perturbations over the study area.

2.3.2. Low-resolution data

NOAA-AVHRR NDVI data were derived from the archives of Nuova Telespazio (Rome) and the University of Berlin within the framework of the EU projects RESMEDES (Remote sensing of Mediterranean desertification and environmental stability) and RESYSMED (Synthesis of change detection parameters into a land-surface change indicator for long-term desertification studies in the Mediterranean area) (Bolle, 1998, 1999). The former archive contained images from 1986 to 1993, and the latter images from 1993 to 2000. The original data were all 10-day NDVI maximum value composite (MVC) images

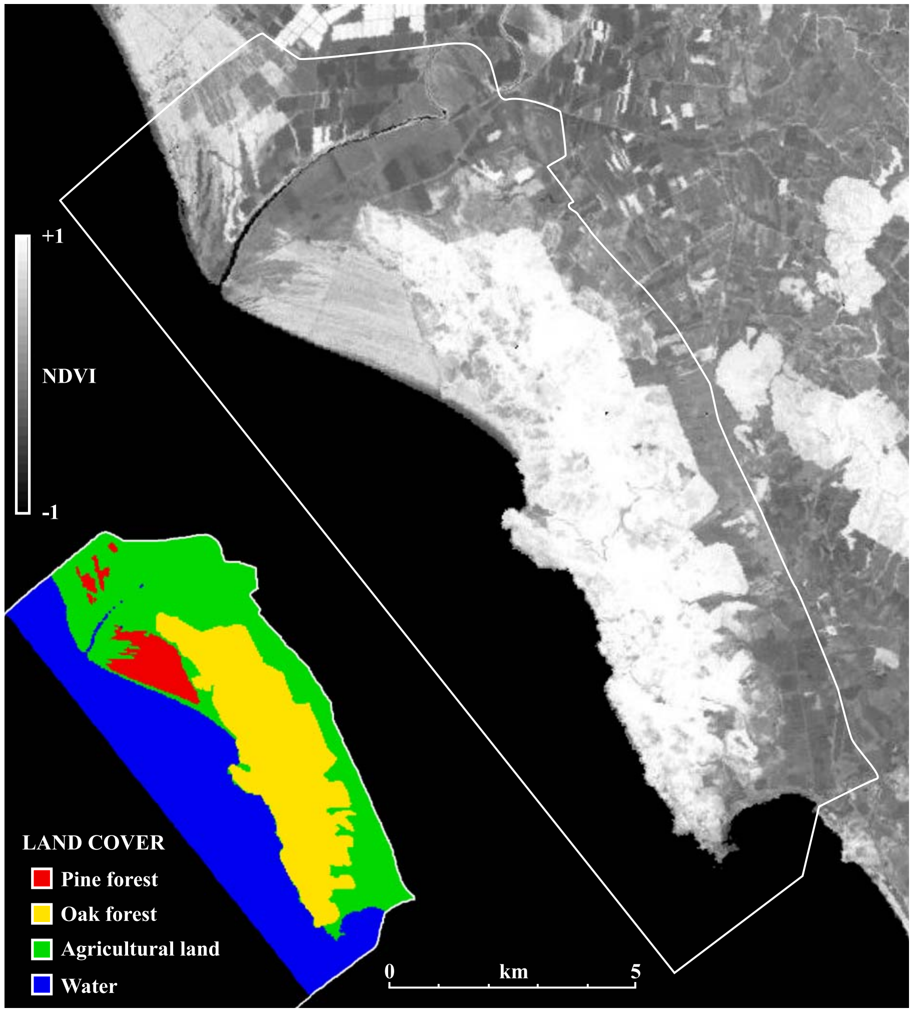


Fig. 2. August 2000 Landsat ETM+ NDVI image showing the boundary of the Natural Park of Maremma and the four main land cover classes considered in the study (from Arrigoni et al., 1985).

mapped in a geographic (Lat/Long) reference system with a 0.01° pixel size. The standard procedure for the production of these data comprised the georeferencing of the original images by a nearest neighbour algorithm, the radiometric calibration of the first two bands to derive apparent reflectances (Koslowsky, Billing & Eckard, 2001), the computation of NDVI values by the conventional formula (NDVI=[B2 − B1]/[B2 + B1]), and the maximum value compositing (MVC) on a 10-day (dekad) basis (Holben, 1986). The final products were therefore thirty-six 10-day NDVI MVC images for each of the 15 available years, with only a gap of about 4 months at the end of 1994 due to actual unavailability of reliable AVHRR data.

Table 1
Landsat 5 TM and Landsat 7 ETM+ images used for evaluating the forest NDVI values derived from low resolution data

Sensor	Acquisition date
Landsat 5 TM	14 August 1988
Landsat 5 TM	7 August 1991
Landsat 5 TM	25 August 1992
Landsat 5 TM	22 April 1993
Landsat 5 TM	2 August 1995
Landsat 5 TM	3 May 1997
Landsat 5 TM	23 August 1997
Landsat 5 TM	9 July 1998
Landsat 5 TM	10 August 1998
Landsat 7 ETM+	16 March 2000
Landsat 7 ETM+	4 June 2000
Landsat 7 ETM+	6 July 2000
Landsat 7 ETM+	23 August 2000
Landsat 7 ETM+	24 September 2000

3. Extraction and evaluation of NDVI data

As mentioned previously, the identification of the spectral properties of relatively small land surfaces from low-resolution images is usually problematic. In the specific case, the rather limited extent of the vegetated surfaces (minor sides of 3–4 km, see Fig. 2) resulted in the presence of many AVHRR pixels partly covered by different vegetation types. While these mixed pixels obstructed the correct identification of forest NDVI values, AVHRR data were anyway unique in providing the sampling frequency and the temporal coverage necessary for long-term studies. The current phase of the investigation was therefore aimed at evaluating the advantages given by an advanced over a conventional procedure to extract the NDVI values of the park vegetation surfaces from AVHRR data. The performances of the two methods were assessed by comparing their outputs to the NDVI estimates derived from the available Landsat TM/ETM+ images. For this comparison, some assumptions were necessary. The first was that the spectral and observational differences between the two sensor types (AVHRR and TM/ETM+) produced only minor effects. The same was assumed for the temporal differences which derived from having taken the TM/ETM+ images in days which were probably different from the AVHRR NDVI maximum value acquisition dates. Both these assumptions were considered reasonable in the present case, where the objective was not an absolute accuracy assessment but the relative evaluation of different data extraction methodologies (Maselli et al., 1998). As finally concerned the approximate linearity in the composition of the NDVI values coming from the different sensors, it had already found to be realistic, producing generally minor and negligible inaccuracies (Kerdiles & Grondona, 1995).

In view of the data intercomparison, both high- and low-resolution satellite images were subjected to a series of preprocessing steps. All Landsat TM/ETM+ images taken in bands 3 and 4 were first georeferenced by means of ground control points, reaching a positional accuracy of about 1 TM/ETM+ pixel (30 m). The images were then radiometrically calibrated by the relevant coefficients (Teillet et al., 2001) and corrected for the atmospheric effect by the method proposed by Gilabert, Conese, and Maselli (1994). The last correction was applied in order to produce high-resolution NDVI images which could also serve for testing the validity of the MVC algorithm in reducing the atmospheric disturbances of NOAA-AVHRR NDVI images. From the atmospherically corrected images, NDVI was computed by the conventional formula NDVI=[B4 − B3]/[B4 + B3].

A preliminary evaluation of the geometric accuracy of the AVHRR NDVI images, carried out by visual comparison to existing geographic vector information (coastlines, boundaries of lakes, etc.), showed a mean error of about 1 AVHRR pixel (1.1 km). The long-term stability and consistency of the Telespazio and Berlin NDVI data series had already been demonstrated in previous investigations (Bolle, 1999; Koslowsky et al., 2001). A visual examination of these images, however, indicated that they contained a variable number of pixels with erroneous values. A specific procedure was therefore applied for the reduction of all these defects, which is fully described in Escadafal, Bohbot, and Mégier (2001). This procedure consisted of a preliminary cosmetic filtering applied to all original 10-day MVCs in order to remove isolated pixels with anomalous NDVI values and replace them with local NDVI averages. Next, since the original compositing algorithm was ineffective to remove all atmospheric contaminations for periods with high cloud cover, a further correction was performed by applying a modified version of the algorithm proposed by White, Thornton, and Running (1997). That algorithm is based on the concept that abrupt decreases in NDVI followed by relatively fast (within approximately two to three 10-day periods) recoveries can be safely attributed to the effects of clouds. These decreases can therefore be removed, and the data series can be reconstructed by a moving average operation. The application of the complete correction procedure yielded 10-day MVC images of a quality which can be considered acceptable for the evaluation of inter-year NDVI variations (Escadafal et al., 2001).

The spatial distribution of the four main land cover classes in the park (coniferous and broadleaved forests, grassland/cropland, and water, see Fig. 2) was derived from the vegetation map of Arrigoni et al. (1985). From this map, digitised with the resolution of the TM/ETM+ data (30 m), it was found that pine wood covered 7.5% of the park land surface (7756 pixels), while oak forest and grassland/cropland covered 39.5% and 53.0% of this surface, respectively (40,682 and 54,524 pixels). The digitised map was used to calculate the relevant average NDVI values of the three vegetation classes in all available 14 TM/ETM+ scenes. The same map was then resampled into the AVHRR reference system, obtaining area estimates of the three classes only slightly biased with respect to those from the higher resolution data (8.7%, 39.8%, and 51.5% respectively, equal to 9, 41, and 53 pixels). The use of this low-resolution map allowed the computation of 14 mean NDVI values for each vegetation class as simple averages of the relevant pixels. This conventional computation of course suffered from the previously seen geometric inaccuracy and the mixed pixel problem and was expected to provide only approximate NDVI estimates of the different vegetation types.

A more sophisticated method was therefore tested in order to better separate the NDVI signal of the forests from that deriving from the other cover classes. This method is based on the computation of locally calibrated multivariate linear regression models which can determine spatially variable NDVI estimates of all land cover types derived from a higher resolution map (Maselli, 2001). That method extrapolates for every image pixel different multispectral (or multitemporal) end-members, which represent the signatures of all pure classes considered. As demonstrated in the same work, these spatially variable end-members can well reproduce within-class NDVI variations and are generally more suitable than conventional end-members for the description of local vegetation properties. The implementation of the method was carried out as follows. The vegetation map was first converted into four abundance images superimposed on the AVHRR images (Kerdiles & Grondona, 1995). These were used to find spectrally variable end-member images by applying the locally calibrated multivariate regression procedure to the same eighteen 10-

day NDVI MVCs as before. The mean NDVI end-member values of the three vegetation classes in these MVC images were finally computed using the same reference map as done previously.

The results of the comparison between the NDVI values derived from high-resolution images and those obtained from the AVHRR data by the two computation methods are visible in Fig. 3A and B. From these figures, the different ranges of the NDVI values from the two sensors can be immediately noted, which were presumably due to the different correction levels applied to the relevant original data (i.e., NDVI computed from not atmospherically corrected images in the case of AVHRR and from atmospherically corrected images in the case of TM/ETM+). This indicates that, as expected, the MVC algorithm was only partly capable of removing the atmospheric effect from NDVI data (Holben, 1986). More importantly, the extraction of NDVI values from AVHRR data by simple average was rather ineffective, as their correlation with the TM/ETM+ values was quite low ($r = 0.602$). The use of the end-member identification procedure led to a decisive improvement in the correlation between AVHRR and TM/ETM+ NDVI values ($r = 0.867$), which indicated that such procedure was capable of correctly approximating the latter values at the spatial scale of the vegetation covers in the Park.

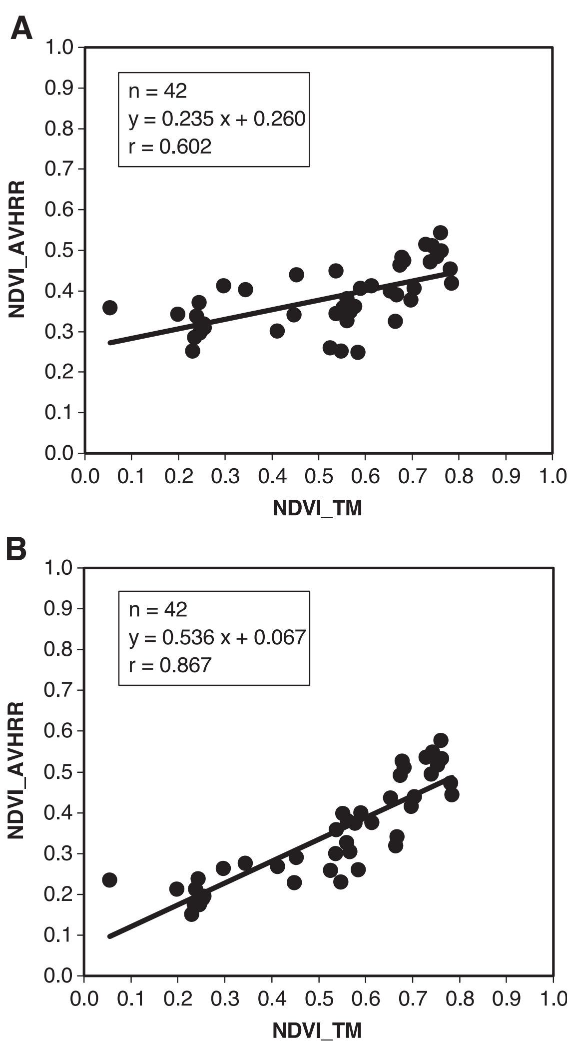


Fig. 3. (A and B) Regressions between the NDVI values of the three vegetation classes in the park (pine and oak forests and agricultural land) derived from Landsat TM/ETM+ data and extracted from AVHRR images by conventional averaging (A) and by applying the end-member identification method (B). Both correlation coefficients are highly significant ($P < 0.01$).

4. Application of trend analyses to the forest NDVI data

The availability of a method to extract accurate NDVI values of the different vegetation covers within the park allowed the analysis of the forest NDVI profiles over the whole study period (from 1986 to 2000). To this aim, the end-member identification method described previously was applied to all available 10-day composites obtaining multi-year NDVI profiles of the pine and oak forests. The mean 10-day NDVI profiles of the two forests computed over the 15-year study period are shown in Fig. 4A and B. As can be seen, both these profiles are typical of Mediterranean woody vegetation, with an NDVI peak in late spring/early summer, but some important differences existed between the pine and oak forests. The mean NDVI profile of the former has in fact more xerophic features, showing a primary peak in late spring and a secondary peak in early fall due to the concurrence of favourable thermal and hydric conditions, and two minima in winter and summer due to unfavourable cold and arid conditions, respectively. The mean NDVI profile of oak forest has instead a unique maximum in early summer and a unique minimum in winter, which indicates the absence of a clear summer dry period and more temperate climatic features.

Possible consistent variations occurred in the green biomass of the two forest areas during the 15 years considered were highlighted by linear trend analyses performed over the NDVI profiles of each 10-day period. The results obtained by these regression analyses are summarised again in Fig. 4A and B as slope coefficients, which are indicative of the mean linear NDVI variations during the study period. As can be seen, almost all slopes are negative for both forest areas, indicating general decreases in NDVI values. The NDVI decreases were, however, remarkably higher for the pine forest during almost the whole year. The decreases occurred in this class had a clear seasonal pattern, being nearly null in winter–spring and remarkable in summer and early fall. The first negative peak approximately coincided with the summer NDVI minimum, when local vegetation development was limited by adverse hydric conditions.

An exemplification of the trend analyses performed is shown in Fig. 5 for one of the 10-day periods with highest

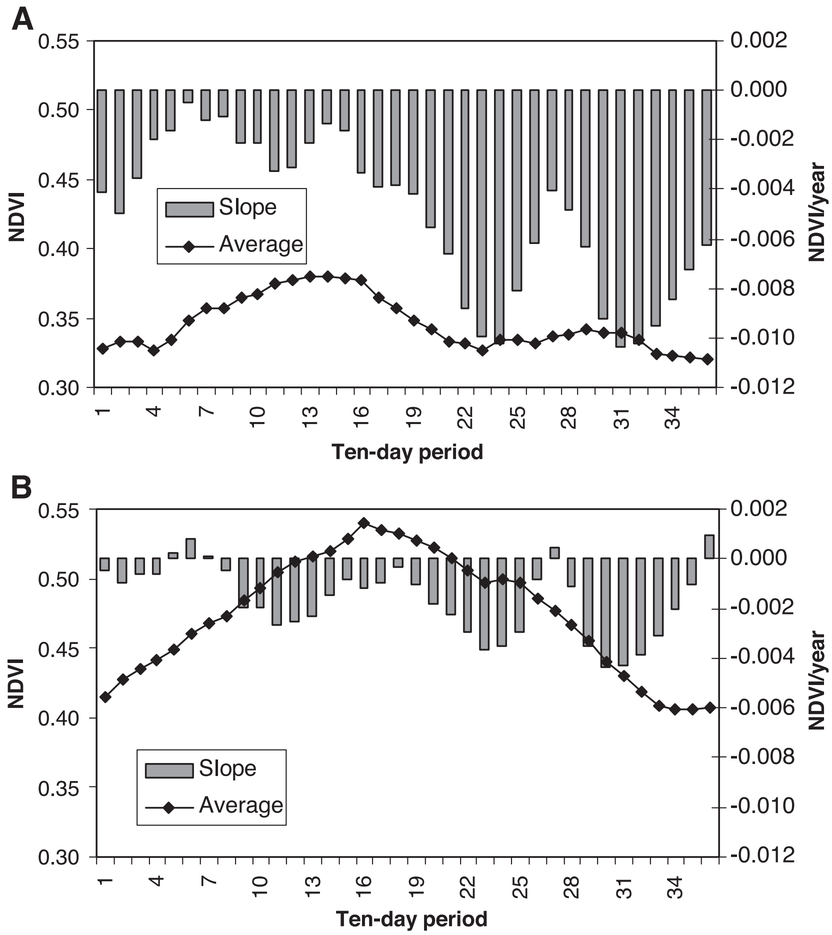


Fig. 4. (A and B) NDVI averages and slopes of the 10-day periods from 1986 to 2000 computed for the pine (A) and oak (B) forests.

negative trends (the second 10-day period of August). As can be seen, the negative slopes of the two forest classes were due to both the quite regular NDVI decreases in the 15 years considered, which determined relatively high negative correlation coefficients, and to the large NDVI range in the same period. Most of these negative trends were actually determined by the particularly high and low NDVI values at the beginning (1986–1989) and end (1999–2000) of the study period, respectively. All these features were much more evident for the pine forest, which, as previously noted, had also globally lower mean NDVI values.

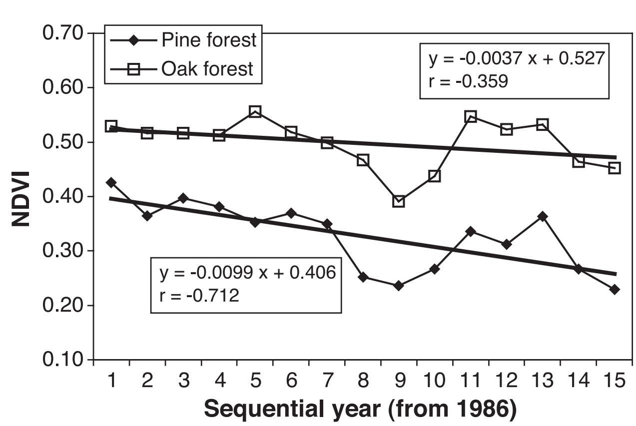


Fig. 5. Examples of the NDVI trends and fitted linear regressions for the oak and pine forests in the second 10-day period of August.

5. Analysis of the possible causes of the NDVI variations found

On the basis of the previous results, the investigation proceeded towards the identification of the possible environmental causes of the negative NDVI trends found, which were particularly notable for the pine wood in late summer and fall. In this direction, it was preliminarily hypothesized that the 2 months of maximum negative NDVI trends (August and November) might have interrelated values, i.e., the second mostly depended on the first. It is actually well known that any cause of vegetation stress may prolong its effect to the following months, when vegetation can not recover completely (Odum, 1973). This hypothesis was currently substantiated by the relatively high, statistically significant correlations existing between the NDVI values of August and November in the 15 study years for both coniferous and broadleaved forests ($r = 0.791$ and 0.527, with $P < 0.01$ and $P > 0.05$, respectively). Attention was therefore focussed on the primary August negative peak, which was also much more interesting from an environmental viewpoint than the secondary November peak because of the relevant higher plant transpiration and photosynthetic activity.

The search for the causative agent of the August NDVI decreases started from the consideration that, being the forest areas protected, no human intervention could directly deteriorate these ecosystems. The thinning and cutting operations which were carried out in the area during the study period in fact concerned only small forest surfaces, where vegetation generally recovered quickly. Another possible cause, soil salinization, was also known to affect only small pine-wood plots placed in inter-dune depressions, with negligible effects at the park scale (Maracchi, Conese, Maselli, & Bravetti, 1996). The same can be said for coastal and soil erosions, which affected only small forest areas (Innocenti & Pranzini, 1993). As regards wildfires, no notable event was recorded in the same period (Regione Toscana, 2001). Keeping in mind the previously mentioned studies on ongoing climate changes, the most likely cause was therefore hypothesized to be of meteorological origin and, in particular, a possible diminution of rainfall similar to those already recorded in several Italian regions (Brunetti et al., 2000; Buffoni et al., 2003). Being in fact temperatures throughout the whole year mild and with limited inter-annual variations, the rather scarce and irregular rainfalls are the primary limiting factor for vegetation growth in the area (Rapetti & Vittorini, 1995).

It therefore remained to ascertain if increasing dryness actually occurred during the 15 study years, which was pursued by analysing the rainfall data measured at the meteorological station of Alberese. In particular, trend analyses similar to those applied to NDVI were performed on the 10-day rainfall sums of the study period (1986–2000). In this case, a running average with a moving window of nine 10-day periods (3 months) was first applied to the original data in order to reduce excessive irregularities which are typical of rainfall events and could disturb the identification of linear trends. The results of the analyses are shown in Fig. 6, which also reports the filtered rainfall averages for the 36 annual 10-day periods. From this figure, it can be seen that, as expected, the rainfall maximum (about 27 mm/10-day period) coincided with fall, followed by a period of rather constant medium rainfall up to early spring. More importantly, clear negative trends were present, concentrated in two periods, the primary in winter (from January to March) and the secondary in late summer–early fall (from September to November). Since rainfall in fall and winter determines soil water recharge, these trends, which were of high absolute values (up to 1.2 mm/year for each 10-day period), could originate the water shortages in the last study years that were the likely cause of the previously seen NDVI decreases.

In order to further verify this last hypothesis, correlation analyses were performed between the forest NDVI values of the month with maximum negative trend (August) and the previous 10-day rainfall data, still filtered as in the previous case. These analyses were aimed at looking for statistically significant relationships between inter-year variations in NDVI and previous rainfall which could be indicative of the possible dependence of the former on the latter. For a complete analysis, rainfall data were considered from the November 10-day periods of the previous season (the month of maximum rainfall and therefore soil water recharge) to the August 10-day periods of the concurrent season. The results of these analyses are shown in Fig. 7 for the two forest types. As can be seen, the correlations between inter-year variations of forest NDVI and rainfall were clearly positive and statistically significant ($P < 0.05$) only for pine wood from January to March. Lower, not significant correlations were found for deciduous forest with a positive peak in approximately the same period. In any case, the period of maximum correlations

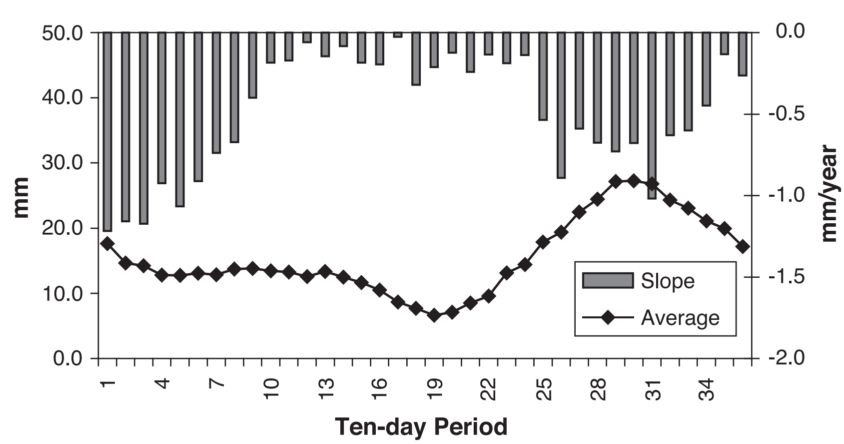


Fig. 6. Rainfall averages and slopes of the 10-day periods from 1985 to 2000 derived from the filtered data of Alberese.

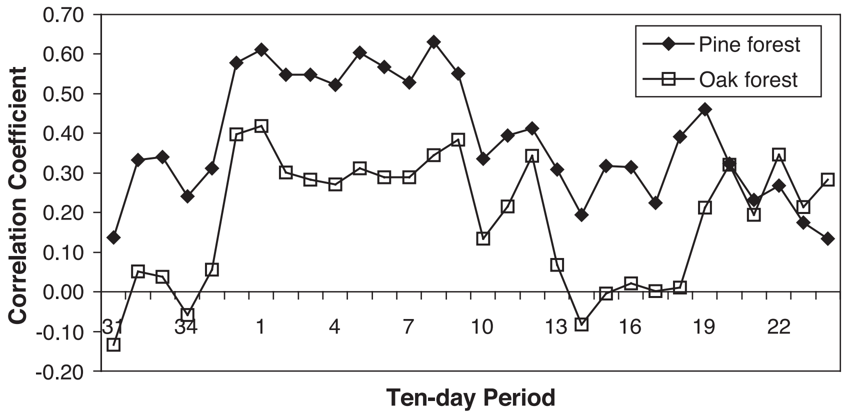


Fig. 7. Correlations between the forest NDVI values of August and the filtered rainfall levels of preceding 10-day periods (from previous September to concurrent August). All r higher than 0.514 are statistically significant ($P<0.05$).

approximately coincided with that of maximum rainfall decrease, as expected if this was the main cause of the found August NDVI diminution.

6. Discussion

The current paper aimed at evaluating the use of remotely sensed data to follow the multiyear evolution of Mediterranean forest ecosystems in a protected area in Central Italy. The first experimental step consisted of testing different methods to extract NDVI values of relatively small forest areas from low-resolution AVHRR images. The optimal method found was then applied to a long-term NDVI data series (1986–2000) in order to obtain NDVI profiles of these forests which could be subjected to trend analyses. These analyses highlighted negative NDVI trends mostly concentrated in summer and fall that were finally explained in terms of the likely cause, i.e., a concurrent, correlated diminution of winter rainfall.

As regards the first phase, the experimental comparison to higher resolution NDVI data confirmed that the end-member identification procedure recently proposed by the author was efficient in extracting pure class NDVI values. This result was of particular importance in the present case due to the limited size of the observed vegetated areas, which commonly gives problems in using low-resolution data because of their inevitable geometric inaccuracy and the predominance of mixed pixels.

The availability of a procedure capable of efficiently extracting forest NDVI values from low-resolution images was a necessary basis to produce accurate long-term NDVI data series characterizing the coniferous and broadleaved ecosystems in the park. Trend analyses applied to these data highlighted consistent NDVI decreases concentrated in summer and late fall, which, being particularly evident for the pine wood, could indicate a possible deterioration of this ecosystem. When looking for the likely cause of these NDVI decreases, clear negative trends were found in the rainfall regime of winter periods, which are consistent with similar patterns recently found in the region by other authors (Brunetti et al., 2000; Buffoni et al., 2003). The fact that water availability is known to be the main limiting factor for local vegetation development led to hypothesize that the rainfall and NDVI decreases were causally linked. This hypothesis was in accordance with the results of previous studies on the use of NDVI data in semiarid areas and was supported by the current experimental finding that August NDVI values were correlated with soil water recharge during preceding winter months.

The identification of rainfall as the main causative agent of the NDVI decreases was supported by the different mean NDVI values and trends found for coniferous and deciduous forests. The existence of a clear summer NDVI minimum for the pine forest in fact indicated its more clear Mediterranean features, with a stronger dependence on summer water availability. These different behaviours were reasonably due to both climatic and edaphic factors, being the pine wood situated in the coastal plain and the oak forest mostly on the southern hills. This implies that, due to the effect of topography, the coniferous forest experienced temperatures which were slightly higher and rainfall presumably lower than those of the adjacent hills. Moreover, soils in the plain were more sandy and had therefore lower water retention capacity than on the hills. Thus, the pine wood ecosystem was expected to be more sensitive to water stress and, consequently, to rainfall reduction, as was actually indicated by the higher and more significant negative NDVI trends found experimentally.

Such an interpretation was also in agreement with the higher and more significant correlations found between summer NDVI values and winter rainfalls for the pine wood with respect to the oak forest. In this regard, it must, however, be noted that part of the lower latter correlations might originate from the relevant lower representativity of the meteorological data collected at the study station. As previously mentioned in fact the oak forest, being placed on the hills, experienced a climate which was presumably slightly different from that in the plain. In any case, these findings testified to the stronger dependence of the pine wood summer NDVI values on winter rainfalls and brought further support to the hypothesis that concomitant decreases in winter rainfall and summer NDVI were causally linked, i.e., the first was the main cause for the latter.

In spite of these coherent experimental results, care must be suggested when interpreting the outputs of trend analyses applied to environmental phenomena controlled by meteorological factors. Such phenomena are in fact intrinsically unstable due to weather vagaries which can determine multiyear environmental variations similar to consistent trends. In particular, the ecological meaning of the NDVI decreases currently found should be interpreted keeping in mind that Mediterranean ecosystems are well adapted to not infrequent multiyear drought spells, from which vegetation can easily recover after some humid seasons (Odum, 1973). Hence, great attention should be used in drawing conclusions about the actual ecological consequences of the increasing forest dryness found in the study period.

7. Conclusions

The work performed was globally successful in showing the development and possible use of a methodology to extract and analyse multiyear NOAA-AVHRR NDVI data of relatively small forest ecosystems. Such analysis can have important ecological implications, since, as already noted, the index is directly linked to both vegetation green LAI and FAPAR. Being these functionally connected to plant transpiration and photosynthesis, variations in NDVI become indicative of variations in these processes which are essential components of the land water and carbon budgets (Waring & Running, 1998). Hence, the analysis of NDVI data assumes a particular relevance not only for monitoring local vegetation conditions, but also to assess possible changes in the use and accumulation of water and carbon at different spatial scales.

The method developed could actually be applied to wider areas with known land cover in order to provide information on vegetation conditions useful by itself or as input for simulation modelling techniques (Waring & Running, 1998). In all these cases, however, the meanings and implications of the obtainable results should be carefully evaluated in relation to other information on local vegetation conditions derived from conventional sources (meteorological data, reports on forestry activities, ground surveys, etc.). More specifically, remote sensing techniques could be used to monitor large vegetated areas and identify ‘‘hot spots’’ where more in-depth analyses should be conducted. In this way, eco-physiological measurements, which are necessary to ascertain the state of local vegetation but are expensive and time consuming when applied to large areas for long time periods, could be restricted to particular, environmentally representative situations.

As specifically regards the case study area, the current investigation showed that both coniferous and broadleaved forest ecosystems in the Natural Park of Maremma suffered from a water stress period during the 15 years from 1986 to 2000. This clearly suggests the importance of further studies directed to ascertain the future development of this drought spell and its possible environmental effects within the Park and in surrounding areas. More generally, the discovered dependence of forest NDVI values on winter rainfalls assumes a particular relevance in view of the climate changes already occurring and expected in the Mediterranean basin during the next decades (Palutikof et al., 1994). Since ecosystems with similar characteristics are widespread in Mediterranean coastal areas, this dependence might lead to extended variations in vegetation conditions which should be properly taken into consideration within the present debate on the environmental and economic consequences of ongoing global changes.

Acknowledgements

The author thanks Dr. L. Fibbi and Dr. D. Grifoni for their assistance in the analysis of the rainfall data. Thanks are also due to Prof. H.J. Bolle and Prof. M. Innamorati for their useful comments on the first draft of the paper. The author finally wants to thank two anonymous RSE referees for their useful comments on the original manuscript.

References

Arrigoni, P. V., Nardi, E., & Raffaelli, N. (1985). *La vegetazione del Parco Naturale della Maremma (Toscana)*. Università degli Studi di Firenze, Dipartimento di Biologia Vegetale, Internal Report.

Bannari, A., Morin, D., Bonn, F., & Huete, A. R. (1995). A review of vegetation indices. *Remote Sensing Reviews*, *13*, 95–120.

Baret, F., & Guyot, G. (1991). Potentials and limits of vegetation indices for LAI and APAR assessment. *Remote Sensing of Environment*, *46*, 213–222.

Bolle, H. J. (1996). The role of remote sensing in understanding and controlling land degradation and desertification processes: The EFEDA research strategy. In J. Hill, & D. Peter (Eds.), *The use of remote sensing for land degradation and desertification monitoring in the Mediterranean basin. State of the art and future research* (pp. 45–77). Luxembourg: Directorate-General Science, Research and Development, European Commission.

Bolle, H.J. (1998). *Remote sensing of Mediterranean desertification and environmental changes*. Final report of RESMEDES-ENV4-CT95-0094, Firenze (Italy), March 1998.

Bolle, H.J. (1999). *Synthesis of change detection parameters into a land-surface change indicator for long term desertification studies in the Mediterranean area*. Final report of RESYSMED-ENV4-CT97-0683, Firenze (Italy) and Munchen (Germany), December 1999.

Brunetti, M., Maugeri, M., & Nanni, T. (2000). Variations of temperature and precipitation in Italy from 1866 to 1995. *Theoretical and Applied Climatology*, *65*, 165–174.

Buffoni, L., Brunetti, M., Mangianti, F., Maugeri, M., Monti, F., & Nanni, T. (2003). Ricostruzione del clima italiano negli ultimi 130 anni e scenari per il XXI secolo. *Proceedings of the Workshop "CLIMAGRI–Cambiamenti climatici e Agricoltura", Cagliari (Italy), 16–17 January 2003*.

Cannizzaro, G., Maselli, F., Caroti, L., & Bottai, L. (2002). Use of NOAA-AVHRR NDVI data for climatic characterization of Mediterranean areas. In N. A. Geeson, G. J. Brandt, & J. B. Thornes (Eds.), *Mediterranean desertification: A mosaic of processes and responses* (pp. 47–54). The Atrium, Southern Gate, Chichester, West Sussex PO19 8SQ, UK: Wiley.

Caroti, L., Maselli, F., & Serafini, C. (1995). Valutazione dell'informazione agrometeorologica contenuta in profili NOAA-NDVI. *Proceedings of VII AIT National Congress, Chieri (Torino, Italy), 17–20 October 1995* (pp. 487–492).

Davenport, M. L., & Nicholson, S. E. (1993). On the relation between rainfall and the Normalized Difference Vegetation Index for diverse vegetation types in East Africa. *International Journal of Remote Sensing*, *14*, 2369–2389.

Escadafal, R., Bohbot, H., & Mégier, J. (2001). *Changes in Arid Mediterranean Ecosystems on the Long Term through Earth Observation (CAMELEO)*. Final Report of EU contract IC18-CT97-0155, Edited by Space Applications Institute, JRC, Ispra (Italy), August 2001.

Foody, G. M., & Curran, P. J. (1994). Scale and environmental remote sensing. In G. M. Foody, & P. J. Curran (Eds.), *Environmental remote sensing from regional to global scales* (pp. 223–232). Chichester, West Sussex, UK: Wiley.

Gilabert, M. A., Conese, C., & Maselli, F. (1994). An atmospheric correction method for the automatic retrieval of surface reflectances from TM images. *International Journal of Remote Sensing*, *15*, 2065–2086.

Holben, B. N. (1986). Characteristics of maximum-value composite images from temporal AVHRR data. *International Journal of Remote Sensing*, *7*, 1417–1434.

Ichii, L., Kawabata, A., & Yamaguchi, Y. (2002). Global correlation analysis for NDVI and climatic variables and NDVI trends: 1982–1990. *International Journal of Remote Sensing*, *23*, 3873–3878.

Innocenti, L., & Pranzini, E. (1993). Geo-morphological evolution and sedimentology of the Omrone River Delta (Italy). *Journal of Coastal Research*, *9*, 481–493.

Kerdiles, H., & Grondona, M. O. (1995). NOAA-AVHRR NDVI decomposition and subpixel classification using linear mixing in the Argentinean Pampa. *International Journal of Remote Sensing*, *16*, 1303–1325.

Kogan, F. N. (1990). Remote sensing of weather impacts on vegetation in non-homogeneous areas. *International Journal of Remote Sensing*, *11*, 1405–1419.

Koslowsky, D., Billing, H., & Eckard, M. (2001). Sensor degradation and inter-calibration of the shortwave channels of the AVHRR-NOAA 11/14/16 satellites. *Proceedings of "The 2001 EUMETSAT Meteorological Satellite Data Users' Conference", Antalya, Turkey, 1–5 October 2001* (pp. 107–113).

Lacaze, B., Caselles, V., Coll, C., Hill, H., Hoff, C., De Jong, S., Mehl, W., Negendank, J.F.W., Riesebos, H., Rubio, E., Sommer, S., Teixeira Filho, J., & Valor, E. (1996). *DeMon—Integrated approaches to desertification mapping and monitoring in the Mediterranean basin*. Final Report of DeMon-1 Project, Joint Research Centre of European Commission, Ispra (VA), Italy.

Maracchi, G., Conese, C., Maselli, F., & Bravetti, L. (1996). Assessment of the deterioration of coastal vegetation by means of remotely sensed data. *Journal of Coastal Research*, *12*, 103–111.

Maselli, F. (2001). Definition of spatially variable spectral end-members by locally calibrated multivariate regression analyses. *Remote Sensing of Environment*, *75*, 29–38.

Maselli, F., & Rembold, F. (2002). Integration of LAC and GAC NDVI data to improve vegetation monitoring in semi-arid environments. *International Journal of Remote Sensing*, *23*, 2475–2488.

Maselli, F., Gilabert, M. A., & Conese, C. (1998). Integration of high and low resolution NDVI data for monitoring vegetation in Mediterranean environments. *Remote Sensing of Environment*, *63*, 208–218.

Millington, A. C., Wllens, J., Settle, J. J., & Saull, R. J. (1994). Explaining and monitoring land cover dynamics using multitemporal analysis of NOAA-AVHRR imagery. In G. M. Foody, & P. J. Curran (Eds.), *Environmental remote sensing from regional to global scales* (pp. 223–232). Chichester, West Sussex, England: Wiley.

Myers, V. I. (1983). Remote sensing applications in agriculture. In R. N. Colwell (Ed.), *Manual of remote sensing* (2nd ed.), *vol. II* (pp. 2111–2223). American Society for Photogrammetry, Falls Church, Virginia 22046: Sheridan Press.

Odum, E. P. (1973). *Fundamentals of ecology* (3rd ed.). Philadelphia: Saunders, 1971, 574 pp.

Palutikof, J. P., Goodess, C., & Guo, X. (1994). Climate change, potential evapotranspiration and moisture availability in the Mediterranean basin. *International Journal of Climatology*, *14*, 853–869.

Rapetti, F., & Vittorini, S. (1995). *Carta climatica della Toscana*. Pisa, Italy: Pacini Editore.

Regione Toscana (2001), *Programma forestale regionale 2001–2005*. Giunta Regionale, Edizioni Regione Toscana, Firenze, Italy, March 2001.

Richards, J. A. (1993). *Remote sensing digital image analysis: An introduction* (2nd ed.). Heilderberg: Springer-Verlag, 340 pp.

Teillet, P. M., Barker, J. L., Markham, B. L., Irish, R. R., Feodosejevs, G., & Storey, J. C. (2001). Radiometric cross-calibration of the Landsat-7 ETM+ and Landsat-5 TM sensors based on tandem data sets. *Remote Sensing of Environment*, *78*, 39–54.

Thornthwaite, C. W. (1948). An approach toward a rational classification of climate. *Geography Review*, *38*, 55–94.

Townshend, J. R. G. (1994). Global data sets for land applications from the Advanced Very High Resolution Radiometer: An introduction. *International Journal of Remote Sensing*, *15*, 3319–3332.

Veroustraete, F., Sabbe, H., & Eerens, H. (2002). Estimation of carbon mass fluxes over Europe using the C-Fix model and Eruflux data. *Remote Sensing of Environment*, *83*, 376–399.

Walsh, S. J. (1987). Comparison of NOAA-AVHRR data to meteorologic drought indices. *Photogrammetric Engineering and Remote Sensing*, *53*, 1069–1074.

Waring, H. R., & Running, S. W. (1998). *Forest ecosystems. Analysis at multiples scales* (2nd ed.) (p. 55). San Diego: Academic Press.

White, M. A., Thornton, P. E., & Running, S. W. (1997). A continental phenology model for monitoring vegetation responses to interannual climatic variability. *Global Biogeochemical Cycles*, *11*, 217–234.