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Assessment and Examination of Coastal Vegetation Deterioration by Means of Landsat TM Data

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ABSTRACT

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The potential of remote sensing techniques for monitoring natural and agricultural vegetation has already been assessed in a great number of works. The present study is focused on the use of Landsat 5 Thematic Mapper (TM) data as a powerful and efficient means for providing information about a case of coastal vegetation deterioration in Tuscany.

This phenomenon, dating back about twenty-five years ago, mainly concerns the pine plantation which covers the plain south of the outlet of the Ombrone river. In the last forty years this zone has also been affected by strong coastal erosion. The almost contemporaneous occurrence of the two phenomena, as well as the geographical distribution of the disease and some morpho-physiological features of the injured plants, has led to the formulation of an hypothesis which identifies the infiltration of marine salt water into the phreatic surface below the pine wood as the main cause of the deterioration.

In this context, TM data not only provide precise and up-to-date information about the spatial distribution of the disease, but also give a straightforward means for quantitatively assessing vegetation conditions on a local scale (30–50 m.). The latter parameter has been related to the likely causative agent of the injury, *i.e.*, the presence of salt water in the pine wood soil. The results of the investigation confirm the working hypothesis and testify to the actual utility of high resolution satellite data in these situations.

ADDITIONAL INDEX WORDS: *Remote sensing, satellite data, vegetation index, image enhancement.*

INTRODUCTION

The deterioration of natural vegetation is a problem which is becoming increasingly important in many industrialized countries. This phenomenon, which can take different forms, is generally localized in proximity to areas with high anthropogenic pressure and mainly involves tree species, which, due to their long lives, act as integrators of environmental stresses over time (POSTHUMUS, 1985). As proved by many investigations, such diseases are nearly always directly or indirectly caused by anthropogenic actions, such as industrial, agricultural, or urban pollution (BUSSOTTI *et al.*, 1992). In Italy, a typical example is given by the damaged vegetation of the Park of S. Rossore (Tuscany). In this case the pollution of the sea in front of the Park, mainly due to the presence of artificial surfactants in the water, is the most likely cause of the state of vegetation (GELLINI *et al.*, 1983, 1985; INNAMORATI *et al.*, 1987).

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In other situations, however, the causative agents of the damage cannot be identified easily; they are probably connected with both natural phenomena and anthropogenic activity, often carried out in the course of several years (BUSSOTTI *et al.*, 1992). The present research is focused on a case of vegetation disease which has taken place in the Natural Park of Maremma (Tuscany) over the last three decades, mainly concerning the coastal pine wood adjacent to the outlet of the Ombrone river (CONESE *et al.*, 1989a). In particular, the work deals with the possible use of remote sensing techniques in order to monitor vegetation in such situations and to provide a quantitative evaluation of its conditions. For this purpose, ground data have been collected and analyzed in comparison to Landsat 5 Thematic Mapper (TM) imagery. The results show that remotely sensed images not only provide an efficient tool for the visual estimation of the conditions of the pine wood, but also produce a quantitative evaluation of these conditions that can be put in relation with the most likely causative agent of

Figure 1. Geographical position of the study area.

the deterioration, *i.e.*, the infiltration of marine salt water into the soil.

REMOTE SENSING FOR ASSESSING VEGETATION CONDITIONS

Since the launch of the first environmental satellite of the Landsat series in the 1970's, remote sensing data acquired from space have shown great capabilities for monitoring vegetation distribution and condition (HELLER and ULLIMAN, 1983; CURRAN, 1985). From satellite imagery, several vegetation indices have been defined to assess the quantity and quality of active green biomass (HUETE and JACKSON, 1987; WESTMAN and PRICE, 1988a). These indices are generally based on the spectral properties of photosynthetic structures, which strongly absorb light in the red wavelengths of the electromagnetic spectrum and reflect radiation in the near infrared wavelengths (CURRAN, 1985; BARET and GUYOT, 1991). Thus, different light reflectances between near infrared and red can yield different indices, among which the normalized difference vegetation index (NDVI) is widely utilized. In general, the NDVI is defined as:

$$NDVI = (IR - R)/(IR + R) \quad [1]$$

where R = red reflectance of the surface; IR = infrared reflectance of the surface.

NDVI obtained from different sensors has been demonstrated to be highly and positively correlated with Leaf Area Index (LAI) of homogeneous vegetation; and in general, it is a good indicator of vegetation status and density (HUETE and JACKSON, 1987; SPANNER *et al.*, 1990). Clearly, NDVI varies also in dependence of the phenological states of plants, but a value of approximately 0.6 can be assumed as indicative for thick conifers in good vegetative status (WESTMAN and PRICE, 1988a).

Table 1. *Principal characteristics of the Landsat 5 Thematic Mapper.*

Band	Wavelength (μm)	Radiation	Ground Resolution (m)
1	0.45–0.52	blue	30 × 30
2	0.52–0.60	green	30 × 30
3	0.63–0.69	red	30 × 30
4	0.76–0.90	near infrared	30 × 30
5	1.55–1.75	middle infrared	30 × 30
6	10.4–12.5	thermal infrared	120 × 120
7	2.08–2.35	middle infrared	30 × 30

Recently, the advent of high resolution sensors such as the Thematic Mapper (TM) mounted aboard Landsat 5 has brought notable improvements for the assessment of vegetation status at a local scale. This sensor records radiation with a high spatial resolution in seven distinct wavebands which correspond to reflectance of emittance peaks of vegetation (Table 1). Thus, the sensor is specifically suited to detecting vegetation features at a scale of approximately 30–50 m, which is particularly advantageous where the cover types are mixed and heterogeneous. Accordingly, several experimental works have shown the utility of spectral indices derived form TM data for the assessment of forest decline (WESTMAN and PRICE, 1988b; VOGELMANN and ROCK, 1986, 1988, 1989).

STUDY AREA

The natural Park of Maremma, located in the southern part of Tuscany at approximately 42°39′ north latitude and 11°02′ east longitude (Figure 1), covers a surface of about 5,000 hectares. 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 late autumn to early spring. According to the classification of THORNTHWAITE (1948), this climate can be described as mesothermic, between dry-subhumid and semiarid.

The study area corresponds to the sand dunes near the Ombrone delta included in the Natural

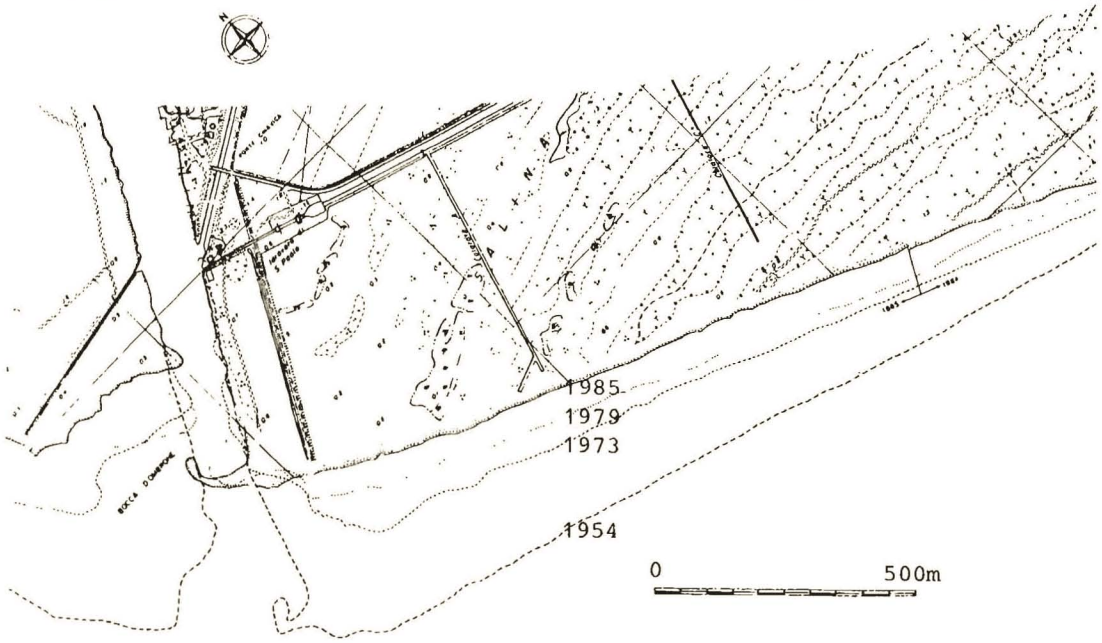

Figure 2. Coastal erosion occurred in the study area from 1954 to 1985.

Park of Maremma. The elevation of the coastal dunes is very low, less than 4 m above sea level. As demonstrated by several investigations, some geomorphological changes have taken place in this area in the last two centuries (BRAVETTI and PRANZINI, 1987; BARTOLINI and PRANZINI, 1985). In particular, the actual shape of the sand dunes and the coastal line in proximity to the outlet of the river is the result of the increasing erosive action of the sea and the decreasing sediment transport of the river (BARTOLINI and PRANZINI, 1985). In the last decades the dynamic relationship between the sea and the river, with its sediment transport, has affected the shape of the outlet of the river, changed from delta to estuary, and the equilibrium between sea and fresh water (Figure 2). Only in the early 1980's coastal erosion began to decrease its intensity, which is at present lower than in the preceding years (2–3 m/year). The sand of the coastal dunes is the only lithological sediment in outcrop in the study area.

According to the vegetation map drawn by ARRIGONI *et al.* (1985), the coastal plain south of the outlet of the Ombrone river was originally covered by three types of botanical associations. Two of them are herbaceous associations; the first, hygroalophilous, is distributed in the depressions near the outlet, whilst the second, hygrophilous, covers the interdunal areas almost parallel to the coastline. The third association is represented by pine wood (*Pinus pinea* L. and *Pinus pinaster* L.), described in the map as evergreen scrubland. This pine wood has artificial origins, as it was planted in the beginning of the 19th century for coastal reforestation, but it adapted well to this kind of environment and developed for about one hundred fifty years. Only in the last two decades has it suffered from marked symptoms of disease which are at present quite evident (CONESE *et al.*, 1989a,b). The trees tend to dry beginning from the lower parts of their canopies, and within a few years, they generally lose their needles completely and die. The phenomenon, at first limited to the zone adjacent to the sea, in the 1980's began to spread towards the inner, lower areas.

RESEARCH PROJECT

As discussed previously, both the geographical distribution and the appearance of the disease are quite peculiar, and this leads to exclude some factors already identified in similar coastal areas as the main cause of the phenomenon. At the same time, these features bring support to the hypoth-

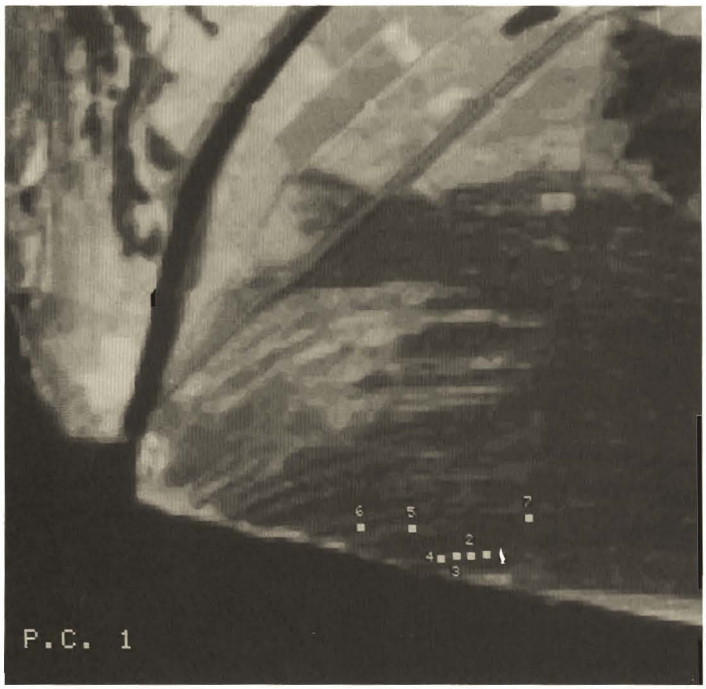

Figure 3. First principal component of the study area (128 × 128 pixels = 3,840 × 3,840 m). The seven pixels corresponding to the sample sites are indicated.

esis that these injuries are related to the infiltration of marine water into the phreatic surface caused by the coastal erosion described (CONESE *et al.*, 1989b). In any case, no research has reported conclusive quantitative relationships between the two phenomena, and no definitive scientific demonstration is available at present.

In this context, TM data can be used to assess vegetation conditions quantitatively and to analyze their possible correspondence with the likely causative agent. Multitemporal satellite data comparisons would be especially interesting; unfortunately, these are impossible now because the TM was launched in 1984, when most of the deterioration had already taken place, while the other Landsat sensor, the MSS, has different spatial and spectral characteristics, which are not suitable for the purpose. Anyway, spatial comparisons can be attempted, based on the knowledge of the original distribution of the healthy pine wood derived from ARRIGONI's vegetation map.

On this basis, the research has been planned so as to correlate the different conditions of the coastal pine wood with the intensity of the cause assumed as working hypothesis, *i.e.*, soil water salinity. The preliminary works has been developed in two phases: (1) Collection and analysis of soil water samples in the pine wood, and (2) Extraction and processing of TM images.

Finally, a quantitative comparison has been made between the two kinds of data in order to ascertain the actual existing relationships.

MATERIALS AND METHODS

Collection and Analysis of Soil Water Samples

The water samples were collected in sites within the pine wood as resulting from the vegetation map of ARRIGONI *et al.* (1985), and from direct ground survey; thus, only the surfaces which were originally covered by this kind of wood were taken into account in the subsequent parts of the research. This homogeneity in the original soil coverage is clearly a necessary condition to evaluate the effects of various soil water salinities on vegetation status by remote sensing techniques, because generally different vegetation types show different spectral responses.

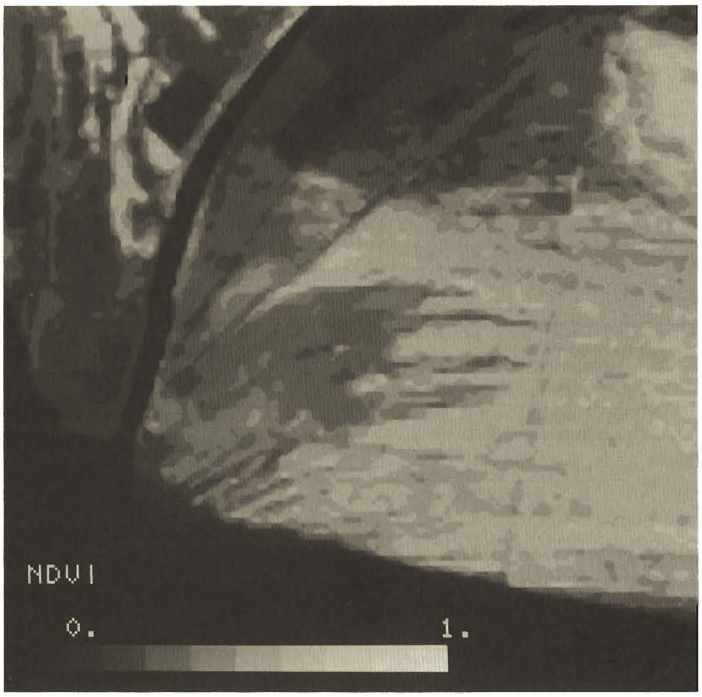

Figure 4. NDVI levels of the same area as above.

Seven samples of ponding water were collected in seven pine wood sites with different vegetative conditions on 26th April 1990; the location of the seven sites is shown in Figure 3. Even if small, this number of samples was deemed sufficient for a first quantitative test of the working hypothesis. Actually, the water samples were collected two days after a notable rainfall event, so that the amount of water evaporated could be considered negligible. About 300 cc from each sampling site were collected and stored for subsequent analysis. Since the results of previous investigations had ascertained that the salinity of the water can be surely ascribed to its marine origin (CONESE *et al.*, 1989b), the present analysis assessed only water chlorine content as an indicator of the intensity of sea water contamination; the analysis of chlorine content was made using Wolhard's volumetric method.

Extraction and Processing of the TM Data

For the current research a TM scene of 128 × 128 pixels was used, extracted from the frame 192/30, Quarter 4, taken on the 1st October, 1988. This was the good quality passage closest to the date of ground sampling among those available in autumn; this season was selected bearing in mind the relevant phenological stage of vegetation, which should allow an optimum contrast between evergreen and deciduous species, with a scarce influence of soil moisture content because of the preceding long arid season (CONESE and MASELLI, 1991). Actually, no rain had been registered in the area during ten days previous to the satellite overpass. The assumption of no substantial modification in the condition of the pine wood throughout eighteen months can be considered quite realistic, considering the present, low intensity of coastal erosion.

After the extraction of the TM scene, the digital counts of its six reflective bands were converted into reflectance values by means of a method previously developed (GILABERT *et al.*, 1993), so that the information obtained could be evaluated more objectively and more easily compared with that of other investigations. The procedure of GILABERT *et al.* is capable of correcting TM reflective images for the atmospheric effect without the use of information external to the satellite data which is difficult to achieve in retrospective studies. The

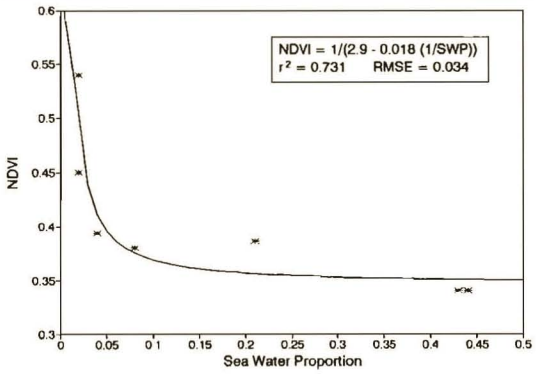

Figure 5. Relationship between sea water proportion in the seven samples and NDVI of the corresponding TM pixels. The hyperbolic curve derived from the regression of Figure 6 is also shown with relevant statistics.

method is based on the identification of dark points in TM Bands 1 and 3 and generally produces reflectance estimates which are accurate enough for operational applications (MASELLI *et al.*, 1993).

To visually evaluate the main features of the study area, a principal component transformation was carried out using all six reflective channels (HORLER and AHERN, 1986). Figure 3 reports the first principal component of the TM scene, which accounts for about 75% of the total information.

From the atmospherically corrected Bands 3 and 4, an NDVI image was generated by means of the formula (Figure 4):

$$NDVI = (R4 - R3)/(R4 + R3) \quad [2]$$

where R4 = surface reflectance in TM band 4; R3 = surface reflectance in TM band 3.

The NDVI values of the pixels corresponding to each group sample site were then extracted from the image. Only one pixel for sample site was considered to fully exploit the resolution of the TM sensor in this situation of high spatial variability. Since geometric accuracy in the identification of the pixels corresponding to the water samples was crucial, the process was accomplished by careful examination of the TM principal components. Each of the seven pixels was therefore individually identified in the study scene taking into consideration all the contextual information which can be exploited by visual interpretation (Figure 3). In this way, the positioning errors which could derive from the geo-referencing of the images by means of ground control points were reduced as far as possible.

Table 2. *Sea water samples collected in the pine-wood: distance from the coastline, chlorine concentration and proportion of chlorine content with respect to sea water.*

Sample	Distance from the Coastline (m)	$[Cl^-]$ (Eq/l)	$[Cl^-]/[Cl^-]$ sea water
1	150	46.0×10^{-3}	0.08
2	130	116.0×10^{-3}	0.21
3	120	246.0×10^{-3}	0.44
4	80	237.0×10^{-3}	0.43
5	220	11.9×10^{-3}	0.02
6	180	22.0×10^{-3}	0.04
7	400	11.0×10^{-3}	0.02
Sea water		550.0×10^{-3}	1.00

The NDVI values found were used to draw a graph against the relevant sea water proportions derived from the chemical analysis (Figure 5); the significance of the relationship was tested by linear and non-linear regression analyses.

RESULTS AND DISCUSSION

The results of the water analysis are reported in Table 2. Clearly, the samples collected in sites adjacent to the sea are contaminated by sea water; this contamination is nearly absent in samples 5–7 but reaches extremely high levels in samples 3–4 (more than ⅓ of marine water). It can be noted that the salt concentration found in the most saline samples highly exceeds the toxicity thresholds for pine trees and, more generally, for all types of non-halophylous terrestrial vegetation (PANERO, 1987).

The first principal component of the study scene (Figure 3) shows the distribution of the main cover surfaces in the coastal plain south of the river outlet, while Figure 4 allows a first, qualitative evaluation of vegetation density and status; in particular, the pine wood in the inter-dunal depressions near the Ombrone outlet shows levels of vegetation index which are remarkably lower than the usual ones (< 0.35).

The estimation of the possible relationship between soil water salinity and pine wood conditions can be derived from the graph of Figure 5. When examining this figure, it must be borne in mind that all of the water samples had been collected in sites originally covered by pine wood; consequently, the different levels of NDVI can be almost entirely ascribed to differences in pine density and vegetative status. A direct connection is clearly appreciable between soil water salinity and

Table 3. *Correlation coefficients of the linear, bilogarithmic and hyperbolic relations between sea water proportion of the seven samples and NDVI of the relevant pixels (* = significant at the 95% confidence level; ** = significant at the 99% confidence level).*

Relation	r
Linear	0.674
Bilogarithmic	0.855*
Hyperbolic	0.932**

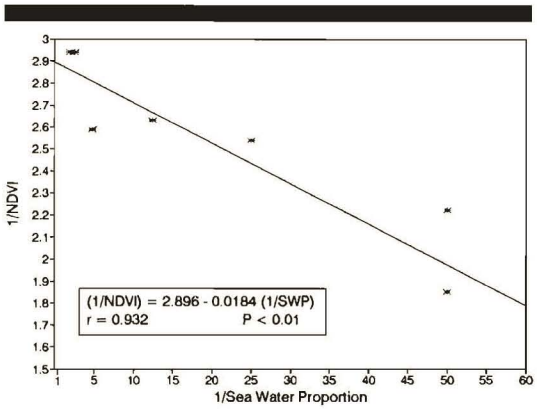

Figure 6. Linear regression between the inverse of the two variables considered in Figure 5, with relevant statistics.

vegetation condition; the samples with higher salinity correspond to pine wood with extremely low levels of NDVI, testifying high levels of damage, whilst the samples with low levels of salinity correspond to points of healthy wood. It may be hypothesized that the residual NDVI values of the damaged sites mainly derives from the contribution of the understory, which can adapt its composition to the salt soil rather rapidly. In effect, the activity of the deciduous vegetation is low in this area at the beginning of October, but it cannot be completely neglected in the interpretation of NDVI data.

Correlation analyses have been performed to test the significance of the relationship found between salt concentration and pine wood NDVI. First, a linear correlation has been attempted (Table 3), which is clearly inadequate to describe the shape of the relation. Accordingly, the correlation coefficient is relatively low and non-significant. A bilogarithmic regression analysis gives better results, with a correlation coefficient which is significant at the 95% confidence level (Table 3). The best result, however, is obtained with a hyperbolic regression which produces a correlation coefficient which is significant at the 99% confidence level (Table 3). For visual assessment, the corresponding linear regression between the inverse variables is shown in Figure 6. Also, the hyperbolic curve found is reported in Figure 5, together with the relevant determination coefficient (r^2) and root mean square error (RMSE). This relationship responds to the Michaelis-Menten law of chemical Kinetics, which could be in good accordance with ecophysiological considerations. Following this interpretation, the effects of sea water on the pine-wood would increase rapidly at relatively low salt levels, indicating the existence of a rather definite threshold condition for the survival of the pine wood (0.03–0.04 marine water). Beyond this threshold, an asymptote would be rapidly reached which corresponds to completely degraded pine trees (saturation phase).

CONCLUSIONS

In the last few decades, natural coastal zones have often been subjected to marked phenomena of vegetation disease, often as a consequence of direct or indirect anthropogenic actions. In order to face these problems, an in-depth knowledge of the relevant ecological aspects and continuous and effective means of environmental monitoring must be achieved.

In this context, the current research is aimed at evaluating the ability of remote sensing techniques to provide information concerning a case of coastal vegetation deterioration dating back to about twenty-five years ago in a natural park of Tuscany. From this work, the following conclusions can be drawn:

(1) High resolution images such as those acquired by the Landsat 5 TM are suitable for mapping vegetation in different conditions at the scale necessary for the identification of local disease (30–50 m).
(2) More generally, remotely sensed data provide an optimum tool for quantitatively assessing such deterioration, so that it can be put in correlation with some likely causative agents with known spatial distribution (water or air pollution, erosion, *etc.*).
(3) In the case under examination, the correlation found brings significant support to the hypothesis that the principal cause of the pine wood deterioration in the Natural Park of

Maremma is the infiltration of sea water into the phreatic surface of the coastal dunes.

Clearly, the final hypothesis can only serve as a basis for further ecological and physiological investigations. However, from a technical viewpoint, these conclusions confirm the potential of the TM for monitoring and assessing the conditions of natural vegetation in highly heterogeneous areas. In practice, the results achieved can be of considerable importance if appropriately taken into consideration for the future environmental management of the Park and of the adjacent zones.

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