Soils and Vegetation Degradation Monitoring in the Mediterranean Basin by the Use of Remote Sensing

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Abstract

The degradation of the permanent semi-natural vegetation and the resulting acceleration of soil degradation and erosion processes constitute important elements of land degradation in the Mediterranean basin. Therefore, under the European Commission's DGXII "Research and Development Programme in the Field of the Environment", emphasis is given to identify, map and control desertification phenomena in the Mediterranean area. While participating to this research programme, the "Environmental Mapping and Modelling Unit" (EMAP) of the Joint Research Centre has initiated the development of methods that permit the use of operational earth observation satellites for detection and repeated monitoring of soil and vegetation characteristics.

As a first important step, a semi-operational approach for mapping soil degradation and erosion damage in Mediterranean environments has been developed under controlled conditions of a well-documented test site in the south of France. It requires radiometric rectification of the satellite data and the availability of spectral measurements of principal soil types (spectral libraries), and can be applied to data from routinely available satellite systems such as Landsat-TM. Linear spectral unmixing is then used to decompose image spectra into their spectrally distinct components, the fractional abundance of which then provides a measure for direct mapping of soil degradation levels and erosion features. Ground verification of the results proved the accuracy of the method. Spectral mixing models also tend to provide less biased estimates of green vegetation abundance than those which are obtained with conventional vegetation indices.

As a further step, requirements are presented for the design of an operational satellite observatory for Mediterranean land degradation monitoring.
Résumé

La dégradation de la végétation permanente semi-naturelle et l'accélération des processus de dégradation et érosion du sol qui en résultent constituent des éléments importants de la dégradation de l'environnement naturel dans le Bassin Méditerranéen. En conséquence, une notable importance est donnée aux efforts pour identifier, cartographier et contrôler les phénomènes de désertification dans l'aire méditerranéenne à l'intérieur du "Programme de Recherche et Développement dans le Domaine de l'Environnement" de la Commission Européenne (DG XII). Dans le cadre de sa participation à ce programme, l'Unité "Cartographie et Modélisation de l'Environnement" du Centre Commun de Recherche travaille au développement de méthodes utilisant les satellites opérationnels d'observation de la terre pour la détection et le suivi d'importantes caractéristiques du sol et de la végétation.

Dans une première étape, une approche semi-opérationnelle de cartographie de la dégradation des sols et de l'érosion en milieu méditerranéen a été développée dans des conditions bien contrôlées et documentées pour un site test du sud de la France. L'approche nécessite la calibration radiométrique des données de satellite et la disponibilité de mesures spectrométriques caractérisant les principaux types de sol, elle peut s'appliquer aux données de satellite disponibles opérationnellement tel que Landsat-TM. La méthode de déconvolution spectrale linéaire (linear spectral unmixing) est ensuite utilisée pour décomposer les données image en composantes spectrales distinctes et les abondances relatives de ces composantes permettent une cartographie quantitative des niveaux de dégradation des sols et d'érosion. Les vérifications sur le terrain ont montré la précision de la méthode. Les modèles de déconvolution spectrale fournissent par ailleurs des estimations d'abondance relative de végétation moins sensibles au substrat que les indices de végétation conventionnels.

Dans une étape suivante sont présentés, les critères pour la définition d'un observatoire méditerranéen pour le suivi par téledétection de la dégradation du milieu naturel.

1. Introduction

Land degradation processes which imply a reduction of the potential productivity of the land (e.g., soil degradation and accelerated erosion, reduction of the quantity and diversity of natural vegetation) are widely spread in the Mediterranean basin. In continuation of a long history of human pressure upon land resources, the main environmental impact results from interactions between climatic characteristics and ecologically unbalanced human interventions which, in the sense of recent definitions of the United Nations Environmental Programme (UNEP, 1991), are often summarised as "desertification processes." An overview of the ecological, physical, social, economic and cultural issues which are collectively contributing to the increasing risk of further degradation of Mediterranean lands has recently been presented by PÉREZ-TREJO (1994).
2. Main sources and processes of Mediterranean ecosystem degradation

The criteria associated with desertification processes, are in some ways influenced by African examples. PEREZ-TREJO therefore concludes that a reconceptualisation of desertification - more appropriate for the European situation - is needed in which the role of urban-industrial expansion, tourism and agriculture in relation to the allocation of water resources are seen as significant contributors to the problem. Inadequate land use practices (e.g., excessive grazing, fuelwood collection, uncontrolled fires) further contribute to the acceleration of degradation processes which result primarily from complex interactions of plant growth and erosion processes. It is now widely agreed that accelerated water erosion is one of the most important sources of soil degradation which, together with the destruction of vegetation cover and structure, contributes to the potential increase of desertification in the Mediterranean basin. Both are often connected, since the degree of soil degradation is in many ways a reflection of the state of vegetation that covers and conditions it (PEREZ-TREJO, 1994). It follows that the most important physical indicators of land degradation in the Mediterranean basin are therefore related to the destruction of soil and vegetation resources.

3. Extension and dynamics of degradation processes

The degradation processes exhibit an enormous spatial variability within the Mediterranean basin: degraded areas are found in the direct vicinity of apparently stable ecosystems, and both, degrading or recovering systems, may occur under a large variety of climatic and physiographic conditions. Understanding whether and where "desertification" in the European Mediterranean is primarily driven by (changing?) climatic conditions or adverse human impact first of all requires a thorough understanding of degradation processes, but also a good knowledge about the spatial extension of stable and endangered ecosystems at regional level. However, although ecosystem processes are intensely studied at numerous field sites in the Mediterranean region (e.g., MEDALUS, 1993) it is not yet clear how findings from field studies at patch-scale can be extrapolated and upscaled to relatively large areas. It is believed that remote sensing systems can significantly contribute to solve this problem. Satellite remote sensing also provides the means for a cartographic inventory of degraded (i.e., environmentally sensitive) areas, and it is virtually the only data source which permits a repeated monitoring of land degradation dynamics.

3.1 Monitoring land degradation with remote sensing systems

Operational earth observation satellites with multi-spectral sensor systems (e.g., Landsat-MSS and TM, SPOT-HRV) are characterised by high spatial (30 or 20 m) and intermediate spectral resolution (6 or 3 bandpasses in the reflective part of the solar spectrum), but have
rather large standard revisit intervals (16-26 days). One of the most important issues is to identify indicators for land degradation processes which have some general applicability to the Mediterranean as a whole, and which can be observed with operational (i.e., spaceborne) remote sensing systems. However, although it is agreed that remote sensing provides a convenient source of information, the problem is that the data collected by these instruments do not directly correspond to the information we need. We must therefore interpret the signal which has interacted with remote objects in terms of the properties of these remote objects (Verstraete, 1994).

3.2 Remotely sensed primary parameters, thematic concepts and derived indices

Engineering data about the detector sensitivity (i.e., calibration coefficients) allow us to reconvert encoded image digital values into measured radiances, and radiative transfer calculations can be used to correct for atmospheric effects, such that the surface-reflected radiance is restored from the satellite-measured signal. Normalizing by the downwelling solar irradiance provides an important primary parameter which is termed "bidirectional reflectance: $p$" (Fig. 1).

![Figure 1. The conversion of satellite raw data into standardized thematic information layers.](image)

Albedo and reflectance changes per se are not direct indicators of land degradation processes, in particular in spatially complex areas like the European Mediterranean. A simple increase in albedo/reflectance might here be due to changes in land surface characteristics (i.e., maturing cereals, non-photosynthetic vegetation, etc.) which do not necessarily imply negative effects. We need then to infer the environmental impact of reflectance/albedo changes by characterising their physical nature in terms of land surface conditions. We thus need an appropriate scene model which can be used to convert multi-
spectral reflectance into thematic information (Fig. 1). A variety of methods have been proposed which range from empirical spectral indices to the inversion of physically-based models; an important prerequisite for their operational use is, in any case, that they must satisfy specific requirements in terms of standardisation and portability.

The development of suitable indices in the context of land degradation monitoring requires a conceptual framework in order to draw conclusions about the land surface conditions. These concepts might vary as a function of regional ecosystem characteristics (i.e., parent material, aridity etc.), but the results from different regions can be consistently evaluated on a higher level, such that the system's susceptibility to further degradation can be assessed by using image-derived, and ancillary information layers. Important conclusions will nevertheless depend on the capability to analyse multi-annual time series through retrospective studies (GRAETZ, 1994).

4. Towards standardized approaches

The most important issue in satellite remote sensing is to conceptualise and streamline the data analysis in a way that consistent indicators for land degradation can be obtained. This implies the development of standardized processing schemes which can be efficiently applied to a variety of landscape types in the Mediterranean basin.

4.1 Radiometric pre-processing issues

They will only be mentioned briefly here, despite their utmost importance. Let us mention that today several radiative transfer codes are available which provide consistent results (e.g., CONEL et al., 1988). Reflectance factor retrievals from the Landsat TM bands have also been achieved with an accuracy of ±0.005 to 0.02 (HOLM, 1989; MORAN et al., 1992; WRIGLEY et al., 1992; MARKHAM et al., 1992), and the same level of precision can be accomplished with atmospheric parameters estimated from scene data (HILL and STURM, 1991; HILL and AIFADOPOLU, 1990). In-flight calibrations for Landsat-TM and SPOT data are also conducted at various high-reflectance sites in order to determine the absolute radiometric calibration gain and monitor the sensor degradation with time (e.g., SLATER et al., 1987; THOME et al., 1993).

4.2 Conceptual framework for the analysis of vegetation and soil conditions

Thematic concepts provide the rational for translating remote measurements of primary parameters (e.g., $p$) into relevant thematic information about vegetation and soil conditions. Ideally, such concepts should be valid for any location in large
ecosystems, but in reality some adaptations might be necessary in order to account for regional variations.

4.2.1 Mapping soil conditions

Eroded soils are often recognised through typical soil colour changes which are due to the removed topsoil. It is nevertheless difficult to define a universally applicable concept which accounts for a variability of soil types and the corresponding sequence of pedogenetic horizons. Our approach refers to basic concepts which consider soil development to be either progressive or regressive with time (BIRKELAND, 1990). Under progressive development, soils become better differentiated by horizons, and horizon contrasts become stronger. In contrast, regressive pedogenesis refers to the addition of material to the surface at a rate that suppresses soil formation (i.e. aeolian dunes, glacial moraines, distal fans, etc.), or the suppression of pedogenesis and the truncation of soil horizons by surface erosion. Both, progressive and regressive pedogenesis cause alterations of the soil surface which, due to corresponding colour changes, are detectable through the wavelength-dependant variations of \( p \) (e.g., BAUMGARDNER et al., 1985; ESCADAFAL, 1994). The intensity of brunification and rubification, and the organic matter content of the topsoil material thus provide important diagnostic features for the spectral identification of a majority of undisturbed Mediterranean soils (e.g., cambisols, fluvisols, luvisols, vertisols, rendzinas). Compared to that, soil erosion produces truncated soil profiles which are characterised by decreasing amounts of iron oxides and organic carbon, while the proportion of parent material increases (e.g., lithosols, regosols). Most parent materials differ spectrally from developed soil substrates, in particular due to specific spectral absorption features and increased albedo levels.

The resulting concept, which is based on the spectral contrast between developed substrates and parent materials, seems to provide a widely applicable framework for relating spectrally detectable surface phenomena to Mediterranean soil conditions, thereby satisfying an important requirement for the successful application of remote sensing techniques (HILL, 1993; HILL et al., 1994a). However, the validity of such concepts has to be carefully analysed in the context of the specific physiographic conditions under which they should be applied. Modifications might be required, for example, in cases of extreme aridity where soil forming processes do not permit the accumulation of noticeable amounts of organic components (e.g., ESCADAFAL, 1994).

4.2.2 Mapping vegetation abundance

Vegetation attributes are usually described by structure, dynamics and taxonomic composition, of which taxonomy is the least important of the three. The classification which is most compatible with remote sensing relates to the projected foliage cover (PFC, or cover) and the life form of the tallest vegetation stratum (GRAETZ, 1990). However, about 75% of the earth's surface is covered by sparse vegetation which transmits the colour of the soil beneath, i.e. the PFC is below 1, in particular in semi-
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Arid ecosystems, such as the Mediterranean. Hence, the soil surface itself should be as much an object of attention as is the vegetation, and the key issue is therefore to provide accurate estimates of green vegetation abundance which are not biased by the spectral contribution of background components (i.e., soils and rock outcrops). Attention should also be given to the spectral characteristics of non-green components of plant canopies and associated plant litters, which largely contribute to the reflectance of terrestrial surfaces in semi-arid ecosystems (Elvidge, 1990). Although we know that the spectral resolution of earth observation satellite systems is not adequate to consistently differentiate between dry plant components and soils, efforts have to be made to resolve ambiguities from the image context (Smith et al., 1990).

4.3 Advanced data interpretation - the spectral mixing paradigm

It results from the previous conceptual considerations that information extraction methods must provide largely unbiased estimates for green vegetation cover, permit the identification of soil related spectral information, and allow sufficient standardisation for multi-temporal monitoring. It has already been argued that traditional multi-spectral classification approaches as well as most vegetation indices are not ideally suited to fulfill these requirements (Hill et al., 1994b). Since the inversion of physically-based bidirectional reflectance models against satellite data is not feasible with currently available data sets, attention is drawn on suitable semi-empirical models.

One of the most promising approaches known as "Spectral Mixture Analysis" - SMA - (e.g., Adams et al., 1989; Smith et al., 1990) assumes that most of the spectral variation in multi-spectral images is caused by mixtures of a limited number of surface materials, and it attempts to model the multispectral reflectance ρ as a mixture of representative "prototype" spectra, the so-called "spectral endmembers" (i.e., vegetation, soil and bedrock components, "shade" as an illumination component, etc.). Spectra can then be "unmixed" by inverting the linear mixing equation:

\[ R_i = \sum_{j=1}^{n} F_j R_{E_j} + \varepsilon_i \text{ and } \sum_{j=1}^{n} F_j = 1 \]

through a least squares regression, while constraining the sum of fractions (i.e., the proportional weights) to one; \( R_i \) denotes the reflectance of the mixed spectrum in band \( i \), \( R_{E_j} \) the reflectance of the endmember spectrum \( j \) in band \( i \); \( F_j \) is the fraction of endmember \( j \), and \( \varepsilon_i \) the residual error in band \( i \). A unique solution is possible as long as the number of spectral components (endmembers) does not exceed the number of bands plus one.

While the "mixing paradigm" is physically meaningful (Craig, 1994), its objective is to isolate the spectral contributions of important surface materials ("endmember abundance") before these are edited and recombined to produce thematic maps (Adams et al., 1989). This approach has been successfully adopted to analyse the spectral
information content related to the erosional state of soils (Fig. 2), but also to derive precise maps of soil conditions and improved estimates of green vegetation abundance from various types of multispectral images (HILL, 1993; HILL et al., 1994a). An essential part of SMA consists in identifying optimised sets of spectral endmembers which are representative for the major variations of regional soil and vegetation conditions. Though endmembers can be retrieved from the image itself, we prefer to choose them from collections of spectroradiometric field- and/or laboratory spectral libraries because there is reason to believe that we can represent the spectral variability in which we are interested by a relatively small number of base categories (i.e., developed soils, fresh or weathered rock outcrops, green vegetation, non-photosynthetic vegetation). The compilation of such "libraries" has already been initiated (ALTHERR et al., 1991), and is being continued in the frame of additional field campaigns in Greece, Spain, France and Italy.

![Figure 2. Ternary plot of about 100 field- and lab-measured soil spectra at Landsat-TM spectral resolution, where the mixing volume is defined by one soil (vertic cambisol) and two bedrock spectra (marls and limestone). Soil conditions range from undisturbed soils (I) to substrates that are increasingly affected by erosion (II-IV) (HILL et al., 1994b).](image)

4.4 Susceptibility analysis through the evaluation of satellite-derived information layers

It is very important to further evaluate temporal changes in soil and vegetation conditions in the context of a more ecologically-based framework. As a first attempt, we have proposed a simplified formalism to combine soil- and vegetation-related information layers (HILL, 1993; HILL et al., 1994a).
Figure 3. Peloponnese, Greece: Comparison of land surface properties based upon a synoptic evaluation of Landsat-derived information layers on soil conditions and vegetation abundance. The numbers refer to "desertification risk levels" in the sense of varying susceptibility to further degradation, ranking from "stable" (1: vegetation cover more than 50% and soil condition index I) to "irreversible degradation" (9: vegetation cover less than 20% and soil condition index IV).

It is based on the fact that, in a more synoptic perspective, an "environmental ranking" of specific soil conditions in Mediterranean ecosystems can be defined as a function of green vegetation cover (because of its protective role), thereby distinguishing for example between regrowth/succession on eroded soils and sparse vegetation cover on well-preserved soil resources (Fig. 3).

The proposed susceptibility index only represents a first attempt to combine image-derived information layers of soil and vegetation conditions through a strictly formalised procedure; it should be revised and further developed in close cooperation with ecologists and specialists from various geosciences. New concepts or findings from detailed field studies are easily integrated by updating the rule base module such that they can be readily applied to new satellite images and archived data products. The incorporation of terrain parameters from digital elevation data (e.g., slope, exposition) appears particularly opportune for obtaining an improved evaluation of ecosystem characteristics, such as water availability or erosion risks.

5. Satellite observatory for mediterranean land degradation monitoring

Finally, we wish to discuss basic elements of a future operational environmental monitoring system for the Mediterranean basin. This requires a concise definition of the
region to be observed, but also includes strategies for implementing efficient processing schemes as a function of existing data types, archives, present and future sensor availability, and overpass cycles. Although this proposal is focused on the use of operational earth observation satellite systems (i.e., Landsat and SPOT), it is believed that existing and future low resolution satellites with more frequent coverage (e.g., the NOAA AVHRRs, the planned vegetation instrument onboard SPOT-4, MERIS, etc.) and active microwave systems (e.g., ERS-1, ERS-2, RADARSAT) should be incorporated at a later stage.

5.1 Operational land degradation mapping and monitoring

In order to better understand the processes of land degradation from their spatial context, it is essential to monitor soil conditions and the disturbance regime of plant communities over time, including their successional recovery. With regard to the available data archives (Landsat-MSS data for European areas are available from 1976, Landsat-TM coverage started in 1983) we wish to particularly emphasise the importance of retrospective studies which may provide the key for understanding the present situation, but also for optimising our approaches for regular monitoring.

Since the retrospective analysis of archived data and regular monitoring are sensitive to the absolute radiance calibration of the sensors, we require practical approaches to minimise the uncertainty about these calibration coefficients. As already mentioned (section 4.1) in-flight calibration coefficients for earth observation satellites are available from specifically designed experiments. Though the coefficients are not continuously updated, they are at least valid for specific periods of the sensor's lifetime. This allows to follow alternative pathways which do not require that each individual scene is radiometrically corrected through radiative transfer calculations. It would be sufficient to apply atmospheric corrections only to reference scenes from so-called "periods of known calibration", and to routinely adjust the radiometry of earlier or later image acquisitions with reference to pseudo-invariant surfaces in the scenes (SCHOTT et al., 1988). This "radiometric rectification" approach has already been successfully applied to a time series of Landsat TM data (HILL et al., 1994a).

5.2 Stratified sampling for environmental monitoring

The regional extension of Mediterranean-type ecosystems is such that even when we limit ourselves to the Mediterranean member states of the European Union, a complete coverage with satellite data is not feasible, in particular for repeated monitoring and for change detection.

Instead, we propose to define a sampling frame of representative sites which accounts for the major physiographic and agro-economic variations within the Mediterranean basin. Such a sampling scheme must be based on the path/row reference system of the Landsat and SPOT orbits, but is to be complemented by stratifying the region into zones with homogeneous climatic and edaphic
characteristics (ecoregions). This is important because any comparative analysis of land degradation dynamics must account for the physiographic variability within the Mediterranean basin. We expect that these ecoregions can be derived largely from the evaluation of already available cartographic documents and topographic data (e.g., Commission of the European Communities, 1985; Council of Europe and Commission of the European Communities, 1987). Each image frame then represents a measurement for analysing how changes in climate, drought, land use and fire regimes generate regional changes in ecosystem processes and patterns which can influence the future progress of land degradation. As such, they may be integrated in a nested hierarchy of aerial units with similar response to desertification ("Desertification Response Units") which has been recently proposed by IMESON et al. (1994).

5.3 Standardized thematic interpretation

The proposed scheme consists of several standardized modules (the ellipsoids in figure 4). Radiometrically rectified satellite images provide the primary parameter $p$ for a given control site, and we then use spectral mixture analysis (SMA) to convert the multispectral surface reflectance into soil and vegetation related information layers. Although a unique set of standard endmembers has been identified which can be used for different areas of primarily carbonatic rocks, it is believed that the spectral unmixing can sometimes be optimised by accounting for regional endmember characteristics (Fig. 4). The conceptual framework presented in section 4.2 may require modifications in view of particular regional conditions, but it looses validity only in areas of extreme aridity.

The "synoptic interpretation" module uses the intermediate information layers (e.g., soil condition index, projected foliage cover) for computing an index of degradation and/or susceptibility to land degradation processes, and the comparison of susceptibility indices from different years will provide evidence of either degradation, stability or recovery on a regional scale. However, an important objective of the thematic interpretation is to separate the rhythmic phenological changes of growth and senescence from episodic "abnormal" alterations introduced by climate or human induced disturbance. We must therefore also incorporate the climatic records in order to understand whether the meteorological situation at the various dates was at all comparable. A flexible monitoring scheme which guarantees a minimum of one scene per successive five-year-interval could be adopted. It should also be avoided to directly compare images from different seasons in order to exclude artefacts due to phenological effects, and to minimise radiometric distortions which result from bidirectional angular effects and illumination differences.
Figure 4. Processing scheme for deriving standardized land degradation indices from Earth observation satellite data.

Conclusions

Options have been presented for monitoring land degradation with remote sensing systems, where, unlike meteorological approaches which concentrate on the exchange of matter, momentum and radiation between the earth's surface and the atmosphere, we have emphasised the importance of thematic interpretation pathways for the characterisation of actual land surface conditions.

We have further illustrated how remotely sensed primary parameters, such as the spectral surface reflectance, can be converted into a standardized characterisation of soil conditions and vegetation abundance by means of a thematic conceptual background based on research in geosciences and ecology. This scheme can be applied to extended regions with specific physiographic conditions (e.g., bioclimate, lithology, soil forming processes, etc.). It can also accommodate varying physiographic conditions from region to region.
The actual data interpretation employs linear spectral mixture analysis as a core element. SMA provides physically meaningful image interpretation following the conceptual framework introduced. Selective editing of the resulting fraction images permits an efficient separation of vegetation and soil related spectral information. This is an important advantage for obtaining more objective estimates of green vegetation abundance, and for mapping substrate-related spectral soil properties more independently from the disturbing influence of sparse vegetation cover or illumination differences. It further holds the potential to be largely standardized in terms of required processing parameters thus minimizing the inputs from individual analysts.

Although a number of standardized processing modules are already available for data analysis within operational schemes, additional efforts are required, in particular for the definition of suitable sampling schemes (i.e. the selection of monitoring sites which are representative for large ecoregions), for extending the thematic concepts for an interpretation of remotely sensed primary parameters as a function of ecosystem characteristics and for the incorporation of ancillary information (climatic records, lithology, topographic information).

Finally, we wish to emphasise the importance of a retrospective analysis of earth observation satellite images which are available for almost 20 years. The integrated interpretation of the satellite-derived information layers, available climatic records and results from detailed field studies may provide a new perspective to understand land degradation processes in the European Mediterranean.

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