Data collection on Mediterranean soils, erosion, land cover and land use with remote sensing satellites

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Etat de l'Agriculture en Méditerranée. Les sols dans la région méditerranéenne : utilisation, gestion et perspectives d'évolution

Zaragoza : CIHEAM
Cahiers Options Méditerranéennes; n. 1(2)

1993
pages 229-249

Data collection on Mediterranean soils, erosion, land cover and land use with remote sensing satellites

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SUMMARY - 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. As a first step for using operational earth observation satellites for repeated detection and monitoring of vegetation and soil characteristics, 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 with Mediterranean characteristics. 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 routinely available data from earth observation satellites (i.e. Landsat TM). Linear spectral unmixing is then used to decompose the image spectra into their spectrally distinct components, the fractional abundance of wich then provides a measure for direct mapping of soil degradation levels and erosion hazards. Ground-verification of the results proved the accuracy of the method. Additionally, spectral mixing models tend to provide less biased estimates of green vegetation abundance than those wich are obtained with conventional vegetation indices.

Key words: Land degradation, soil erosion, vegetation damage, remote sensing, earth observation satellites, spectral mixture analysis, soil condition mapping, green vegetation abundance estimates, land cover mapping.

RESUME - La dégradation de la végétation permanente semi-naturelle et l'accélération de la dégradation du sol et des processus d'érosion sont des éléments importants de la dégradation du sol dans le bassin méditerranéen. Comme première démarche pour utiliser l'observation opérationnelle de la terre par satellite pour la détection répétée et la monitorisation des caractéristiques de la végétation et du sol, une approche semi-opérationnelle a été développée, en vue de cartographier la dégradation du sol et les dégâts de l'érosion dans les environnements méditerranéens et ce, sous des conditions contrôlées dans un lieu de test bien connu ayant des caractéristiques méditerranéennes. Cela exige une rectification radiométrique des données du satellite et une disponibilité de mesures spectrales des pricipaux types de sols (banques de spectres) et cela peut être appliqué aux données disponibles de routine des satellites d'observation de la terre (ex. Landsat TM). La séparation linéaire des spectres est alors utilisée pour décomposer les spectres de l'image dans leurs différentes composantes spectrales, dont l'abondance spectrale apporte alors une mesure pour cartographier directement les niveaux de dégradation du sol et les risques d'érosion. Une vérification des résultats sur le sol a démontré la précision de la méthode. En plus, les modèles de mélange spectraux tendent à donner des estimations moins biaisées de l'abondance de végétation verte que celles qui sont obtenues par les index de végétation conventionnels.

***Mots-clés**: Dégradation du sol, érosion du sol, dégâts sur la végétation, télédétection, satellites d'observation de la terre, analyse du mélange spectral, cartographie des conditions du sol, estimations de l'abondance de végétation verte, cartographie de la couverture du sol.*

Introduction

Being a transition zone between the arid tropics and the more humid (temperate) zones to the north, the Mediterranean basin embodies a variety of topographic, lithologic, edaphic and microclimatic conditions. Only its arid-humid climate with the alternation of hot and dry summers and more humid, cool winter periods provides a generally valuable criterion for delineating Mediterranean ecosystems (Nahal, 1981). It is a sensible environment where the natural vegetation has already been devastated and dramatically modified through several thousand years of human activities (Quezel, 1977). Almost all permanent vegetation one can find today are degraded forms such as maquis, *garrigue* and *matorral*, and, although many of these still form large wooded areas, the remaining quasi-natural vegetation appears highly vulnerable to further destruction.

Presently, the main environmental impact results from the combination of Mediterranean climate and ecologically unbalanced human interventions. The dry summer periods frequently coincide with the occurrence of violent rainstorms, causing average yearly soil losses above 15 tons/ha in more than one third of the Mediterranean basin (Grenon and Batisse, 1989). Such excessive losses of soil, nutrients and seeds from the ecosystem affects the regeneration capacity of the vegetation, and thus drives a principle mechanism of irreversible environmental damage. Inadequate land use practises contribute to the acceleration of these degradation processes. In particular the southern and eastern parts of the Mediterranean basin dramatically suffer from overstocking and illegal timber extraction, while other regions are more heavily affected by the excessive use of water resources through modern agriculture, tourism and urban growth. Since increased human pressure upon the environmental resources appears to coincide with a phase of accelerated climatic change it has become an important task to identify regions at risk of severe degradation.

Environmental data collection with remote sensing satellites

Until recently, the monitoring of natural resources and environmental conditions has been based mainly on traditional techniques, such as direct field observations or the analysis of aerial photographs. With the advent of operational earth resources satellites, however, a repetitive and regular observation of Mediterranean environments from space has become possible. Depending on the analysis strategy (i.e. retrieval of primary parameters through physically-based inversion procedures, or direct mapping of radiance features), the routine interpretation of satellite-derived data requires the design and development of efficient and reliable data analysis methods. These must include pre-processing tools to remove contamination of the satellite signal through combined sensor-atmosphere effects, as well as suitable inversion models and/or direct mapping algorithms.

Land use and land cover mapping

Land cover and land use refer to different concepts. While 'land cover' denotes the natural or artificial coverings of the land surface, 'land use' is related to the management of ecosystems by human society. Since land use is not consistently detectable from remote sensing data, normally a mixture of land cover and land use classes is taken into consideration (Lacaze, 1990).

Land use and land cover maps can be derived from satellite data through different methods. Visual analysis of satellite imagery still remains an efficient mean to obtain maps at scales from 1:1,000,000 to 1:100,000. For example, one of the major tasks of the Commission's CORINE Programme (Coordination of Information on the Environment, established through the Council Decision No. 85/338/EEC, O.J. No. L. 176, 6.7.1985) is the establishment of a computerised inventory of land cover. The methodology consists of computer-assisted (only image enhancement) photo-interpretation of earth observation satellite images the results of which are subsequently digitised.

Digital mapping approaches involve automatic classification algorithms that assign each pixel to a land cover class according to a spectral similarity criterion. The achievable accuracy depends very much upon the complexity of the study region, but the use of multi-temporal data sets may, even in complicated areas, drive the precision of automatic classification products up to 75-80 per cent (Hill and Mégier, 1989).

However, it should be emphasised that visual interpretation and automatic mapping approaches are complementary rather than contradictory to each other, as current JRC studies on automatic updating of the CORINE land cover data base are pointing out.

Mediterranean soils and erosion hazards

Mediterranean land degradation (sometimes also termed 'desertification') mainly results from damages of the vegetation cover due to overgrazing, overtrampling, wood collection, accidental or repeated burning, or inappropriate agricultural practices. Accelerated degradation of the soil resource due to erosion hazards, siltation, salinization and alkalinization of irrigated lands strongly affect health, vigour and reproductive capacity of the remaining plants through the disruption of plant-water relations. If erosion is not stopped, further increase in runoff, sheet and gully erosion on sloping ground will ultimately destroy the productive value of the land (Verstraete and Schwartz, 1991). Mapping and repeated monitoring of degradational processes and erosion hazards forms the basis for drafting and implementing rational development plans for a sustained use of Mediterranean land resources.

The Commission of the European Communities is aware of this problem and, in the 4th Environmental Action Programme 1987-1992 (Official Journal of the European Communities - O.J. No. C 328, 7.12.1987), has recognised for the first time the need for a global approach on soil protection. Meanwhile, a wide range of measures has been implemented which directly or indirectly contribute to the control of soil degradation processes (Nychas, 1991). Mapping efforts have been especially supported under the CORINE programme. Thus the EEC Soil Map of Europe at 1:1,000,000 scale (Commission of the European Communities, 1985) has been recently digitised (Platou *et al.*, 1989), and soil erosion risk in particular is being assessed and mapped at 1:1,000,000 scale across the southern (Mediterranean) region of the Community (Bonfils, 1989; Giordano, 1990). The methodology is based on Wischmeier's universal equation of soil loss, and it combines the main factors such as hydric erosiveness (R), soil erodibility (K) as derived from the EEC Soil Map, slope (S) and vegetation cover (C). This map must be considered as an important first approximation but, similarly to the EEC Soil Map itself, does not provide information on a level of spatial detail that could suit the needs of regional land management. Due to their scale of 1:1,000,000 both maps only provide a spatial representation of zones with prevailing soil types and/or erosion risk classes.

However, assessment and monitoring of land degradation processes and soil erosion hazards requires detailed maps with a spatial resolution that is adequate for an integration with existing topographic maps at local level (i.e. scales 1:100,000 to 1:200,000). This is an essential prerequisite for the precise localization of existing hazards, but is to be considered even more important for monitoring the dynamics of land degradation processes since temporal changes will manifest themselves locally before these effects can also be observed on regional level.

Conventional mapping approaches (i.e. field surveys, air photo interpretation) can not provide a suitable solution, mainly due to high costs, deficient mapping quality in difficult or inaccessible terrain and insufficient standardization and repeatability. In view of these problems and the Commission's interest in obtaining suitable documents (CEC, DGXII, Research & Development Programme in the Field of the Environment, 1991-1994) the "Institute for Remote Sensing Applications" of the Joint Research Centre has initiated the development of a semi-operational approach for detailed mapping of soil degradation and erosion hazards in Mediterranean environments through the use of data from earth observation satellites.

In order to ensure a general applicability to large areas the method should meet the following requirements:

i. Use of routinely available data from operational earth observation satellites.

ii. Standardised pre-processing methods that allow the use of multi-date images (essential for maximising the mapped area and monitoring capabilities).

iii. Standardised processing methods and parameters (essential for reproducibility and portability of the method).

iv. Standardised result format (soil development levels that correspond to international soil taxonomy systems, such as FAO nomenclature).

v. Integration of mapping results with topographic maps of at least 1:100,000 scale.

These standards should ensure that the method provides mapping results that are comparable at least within a regional context. An important aspect of their applicability for environmental management actions is that the results can be directly related to existing topographical data bases. Furthermore, monitoring systems can only be successfully implemented when an identical analysis can be reproduced after several years, depending equally on processing standards and the continuity of the satellite data.

Reflective properties of soils

The upper part of the unconsolidated materials overlying the parent rock is exposed to physical, chemical, and biological weathering processes, which, in time, lead to the development of soils with horizontal layers that are distinguished by variations in composition and physical properties. Unlike pedologists in the field, who may refer to exposed soil profiles permitting the observation of genetic soil horizons and the extraction of samples for laboratory analysis, soil mapping through optical remote sensing is restricted to surface reflectance that can be directly observed from the radiation measurements of the sensor system. Since the characteristics of radiation from a material are a function of material properties, observations of soil reflectance can provide information on the properties and the state of the topsoil. This means, in turn, that only such degradation effects can be mapped that have caused significant changes of the soil surface characteristics.

Typical soil spectra

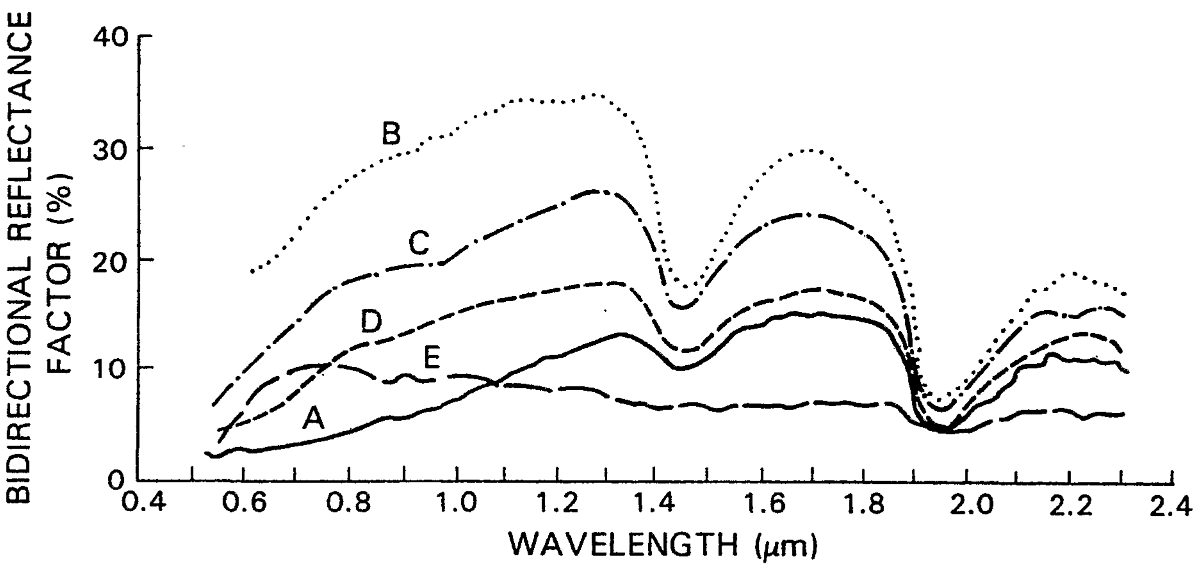
The spectral reflectance of soils is cumulative property which derives from the inherent spectral behaviour of heterogeneous combinations of minerals and organic matter and soil water (Baumgardner *et al.*, 1985; Irons *et al.*, 1989). Numerous studies describe the relative contributions of soil parameters, such as organic matter, soil moisture, particle-size distribution, soil structure, iron oxides, soil mineralogy, and parent material to the reflectance of soils. Stoner and Baumgardner (1981) have defined five distinct soil reflectance types which can be identified by curve shape, the presence or absence of spectral absorption bands caused by organic matter content, iron oxides and soil minerals (Fig. 1). It is believed that any observed soil spectrum resembles one of these spectral curves.

Spectral absorption and reflectance effects in the solar spectrum (0.4 - 2.5 micron) constitute diagnostic features that can be used to directly identify important constituents of soils, such as iron oxides (i.e. hematite, limonite, goethite), clay minerals (i.e. kaolinite, montmorillonite) or carbonates. These are caused by electronic transitions and vibrations in the crystal lattice of, for example, OH-groups (i.e. Al-OH bearing minerals such as kaolinite at 2.2 micron) or carbonates ($CaCO_3$ at 2.35 micron)(Huntington *et al.*, 1989; Goetz, 1992).

However, remote mapping of such reflectance features with optical satellite systems is limited. Many of the spectral absorption features can only be identified with high resolution laboratory spectroradiometers or, at this moment, yet experimental imaging spectrometers aboard research aircrafts. Another major obstacle for using remote sensing data for soil observation is defining the spectral characteristics of soils under a wide range of environmental conditions, such as variable soil moisture, organic matter content, surface roughness and vegetation cover (Fig. 2).

Eroded soils can often be recognised through typical soil colour changes which are due to the removed topsoil. As, for example, erosion of cambisols increases in severity, iron oxides increase and the amount of organic matter decreases (Weismiller *et al.*, 1984). But this may be only a transition state (if erosion has reached the parent rock), and other soil types may, under identical conditions, exhibit different phenomena. It is therefore difficult to define a general methodology for the spectral identification of erosion hazards.

Our approach refers to basic concepts of soil-geomorphic research which considers 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. Pedogenetic processes involve the formation of clay-size particles by weathering of larger grains, the alteration of clay minerals to other clay-mineral species, and the release and accumulation of iron by weathering. Some solids (silt, clay and $CaCO_3$) and ions (Ca^{2+}, Na^+, etc.) dissolved in rainwater are added from the atmosphere, and topsoil organic matter contents increase with the decomposition of plant and animal residues. Transfers within the soil profiles result in the accumulation of silt and clay, Fe, Al, $CaCO_3$, gypsum or halite in the B horizon, or, due to *bioturbation* processes, to the soil surface. In contrast, regressive pedogenesis refers to the addition of material to the surface at a rate that suppresses soil formation (i.e. eolian dunes, glacial moraines, distal fans, etc.), or suppression of pedogenesis by surface erosion.



Curve A: developed, fine textured soils with high (> 2%) organic matter content; B: undeveloped soils with low (< 2%) organic matter and low (< 1%) iron oxide content; C: developed soil with low (< 2%) organic matter and medium (1-4 %) iron oxide content; D: moderately course textured soils with high (> 2%) organic matter content and low (< 1%) iron-oxide content; E: fine textured soils with high (> 4%) iron oxide content.

Fig. 1. Characteristic soil bi-directional reflectance spectra (Stoner and Baumgardner, 1981).

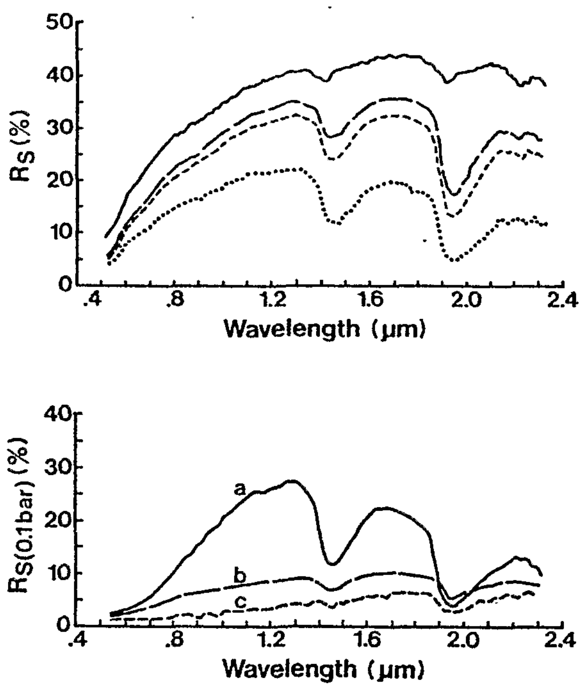


Fig. 2. Spectral (BRF) curves of soils at four different moisture tensions (up) and of three organic soils with different levels of decomposition (down)(Baumgardner *et al.*, 1985).

Both *progressive* and *regressive* pedogenesis causes alterations of the soil surface that, to a certain extent, are spectrally detectable (Fischer, 1991). Following the spectral typology of Baumgardner *et al.* (1985), well developed soils resemble soil reflectance type C and D, while disturbed soils rather correspond to soil reflectance spectrum B (Fig. 1), or exhibit even more pronounced spectral characteristics of the parent rock. In order to map this spectral evidence from earth observations satellite data, suitable processing methods must be developed that are able to compensate for various masking effects, such as partial vegetation cover, illumination and soil moisture differences. Recently, a new technique for multi-spectral data analysis has been developed which seems suited to overcome some of the difficulties mentioned above. It attempts to model spectral reflectance signatures as a mixture of few prototype spectra, and has become known as "Linear Spectral Mixture Analysis" (Adams *et al.*, 1989).

Study sites

The method was developed and evaluated in a well-known test site environment which had been established for several experimental campaigns with airborne imaging spectrometers (Hill and Mégier, 1991; Hill, 1991; Hill *et al.*, 1992). It is located in the southern Ardèche area (44° 20' N, 4° 15' E) in Mediterranean France.

Its climate is sub-mediterranean humid (Bornand *et al.*, 1977), and the site belongs to that part of France where the most erosive rainfalls occur (Fig. 3). It was also selected because its permanent vegetation includes a wide range of Mediterranean oak woods, shrub and rangelands the species composition of which closely resembles that of Mediterranean woodlands in Corsica, Italy, Sardinia and north-east Spain. The dominant tree and shrub species (*Quercus pubescens, Quercus ilex, Juniperus oxycedrus and Buxus sempervirens*) are associated with abundant herbaceous perennials, biennials and annuals. Most of the site exhibits a moderately variable to flat topography with an average altitude of about 200 m, with a single mountain range rising up to 450 m.

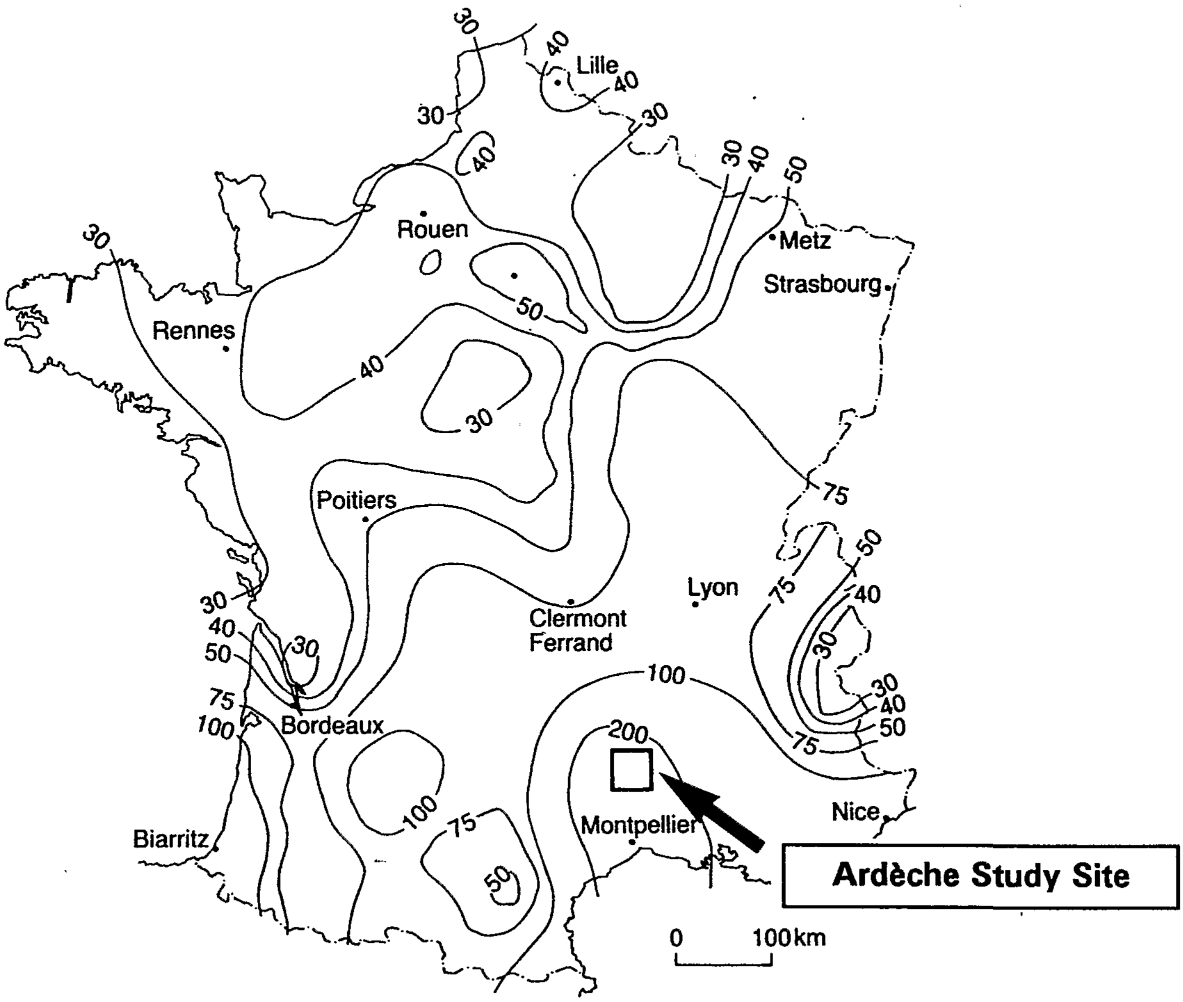


Fig. 3. Mean annual erosivity of rainfalls in France (Morgan, 1986).

Cretaceous to jurassic limestone and marls dominate the lithology of the study site. Undisturbed soils (fluvisols, orthic rendzinas and cambisols) mainly occur on alluvial and fluvial deposits, while most soils on the limestone and marl areas fall into the category of leptosols, being limited in depth by continuous hard rock or highly calcareous material (Bornand *et al.*, 1977; Riezebos *et al.*, 1990). Calcite and quartz are the dominant mineral constituents in most soils, the main accessories being feldspars, kaolinite and illite (Negendank *et al.*, 1990). In particular the marlstone areas include extended locations which exhibit results of frequently occurring, severe soil erosion hazards (badlands).

A first verification experiment is currently conducted in the eastern part of the Peloponnesos peninsula of Greece. Lithologic conditions of this test site partially resemble those of the Ardèche area, but include also other types of parent rock, such as mesozoic sandstones, tertiary sands and conglomerates (Kastanis, 1965). Vegetation is fully Mediterranean, with a dominance of pine forests (Pinus halepensis) and Mediterranean shrublands (phrygana).

Regional soil conditions

An important requirement for soil resources mapping by remote sensing is the careful analysis of regional conditions, existing soil types and its respective climax and degradational forms. It then needs to be verified whether spectral characteristics permit the intended identification. The necessary information can be inferred from existing spectral libraries or specifically conducted radiometric field campaigns.

In the French Ardèche site, the undisturbed soils on fluvial accumulations are mainly calcaric fluvisols with weakly differentiated horizontation. Alluvial sediments, limestone and marl areas with low erosion risk are dominated by soils with rather deep A/C profiles (rendzinas, regosols) which, under favourable conditions, may have developed to cambisols. Brown loamy soils (chromic luvisols, vertic cambisols) can hardly be found *in situ*. They only occur as isolated patches on locations that, for longer periods, have been protected against erosion.

These soil types constitute a regional optimum (climax). A comparison of representative field spectra from the test site and Stoner and Baumgardner's (1981) spectral curves indicate that these soils fall into the transitions between categories C and D (Fig. 4). There is evidence for the presence of iron oxides (spectral absorptions around 0.65 and 0.9 micron), and additional spectral absorptions at 2.2 and 2.35 micron are due to clay minerals (illite, kaolinite) and various amounts of carbonates (Negendank *et al.*, 1990).

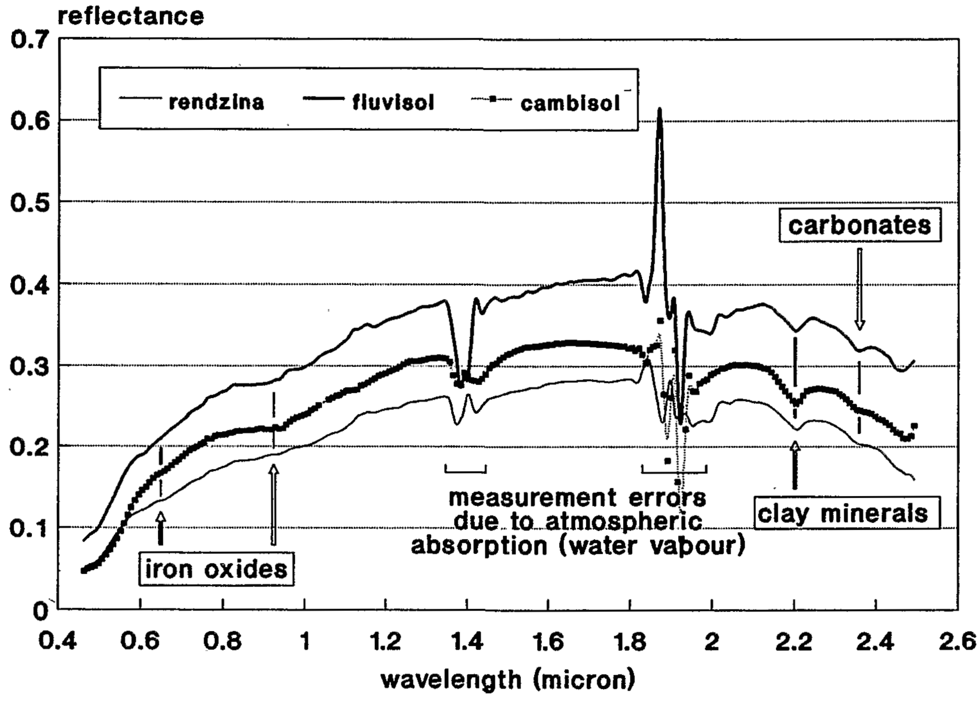


Fig. 4. Field reflectance spectra of fluvisols, cambisols and rendzinas from the Ardèche site, measured with a GER-IRIS spectroradiometer of 2.5 nm spectral sampling intervals (Altherr *et al.*, 1991).

Under less favourable conditions the same types of parent rock have produced only weakly developed soils (various leptosols), or existing soils have, as a consequence of changed environmental conditions, been removed through erosion processes (Riezebos *et al.*, 1990). Due to a deficiency of organic components, the corresponding field measurements reach higher reflectance levels and resemble the spectral curve type D (Fig. 1). The spectra are characterised by strong absorption features of parent rock material (carbonates and clays at 2.35 and 2.2 micron respectively), but there is only weak evidence of iron oxides which can be considered indicators for pedogenetic processes (Fig. 5).

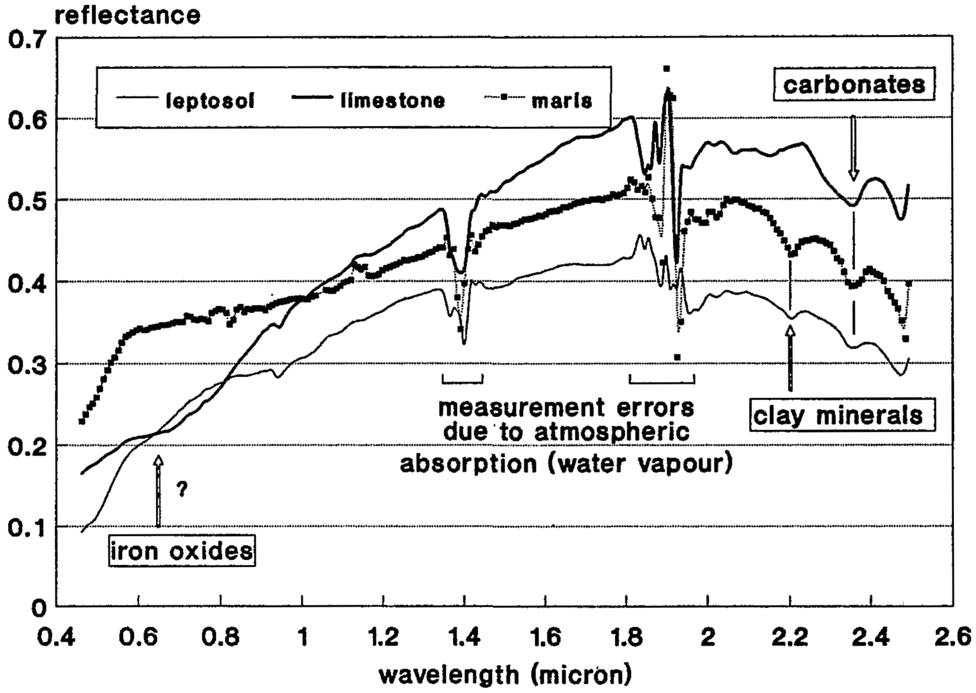


Fig. 5. Field-measured reflectance spectra of leptosols, marls and limestone rocks from the Ardèche site, measured with a GER-IRIS spectroradiometer of 2.5 nm spectral sampling intervals (Altherr *et al.*, 1991).

It seems that the brunification (rubification) of the topsoil constitutes a most important diagnostic feature for a spectral identification of progressive pedogenesis, while eroded or weakly developed soils are rather dominated by spectral characteristics of the parent rock. The existence of such correspondence between spectrally detectable surface phenomena and soil development levels already satisfies a first important requirement for the successful application of remote sensing techniques. But it remains to be analyzed whether the particular sensor characteristics (spectral band position, bandwidth) are adequate for resolving the information contained in the spectral continuum.

Spectral characteristics of the sensor system

Although Landsat MSS data have already been useful for providing information on soil-vegetation site characteristics, a significant advance in resolution of satellite data came about with the launch of an advanced sensor in 1984, the Thematic Mapper (TM), aboard Landsat 4, and one year later aboard Landsat 5. The TM offered a higher spatial resolution (30 m) and additional spectral bands (six bands in the visible and short-wave infrared plus a thermal band) relative to the four spectral bands and 80 m resolution of the Landsat MSS sensor (Irons *et al.*, 1989).

Our primary data set includes four Thematic Mapper scenes of the Ardèche site which have been acquired during 1984 (25 April, 5 July, 30 July and 31 August). A comparison of spectral field measurements in full resolution and convolved to the band passes of the Thematic Mapper demonstrates that important characteristics of the spectral continuum are still preserved, although the narrow absorption features have disappeared (Fig. 6). This implies that the spectral resolution of the Thematic Mapper system might be adequate to directly identify important substrate characteristics on a regional scale.

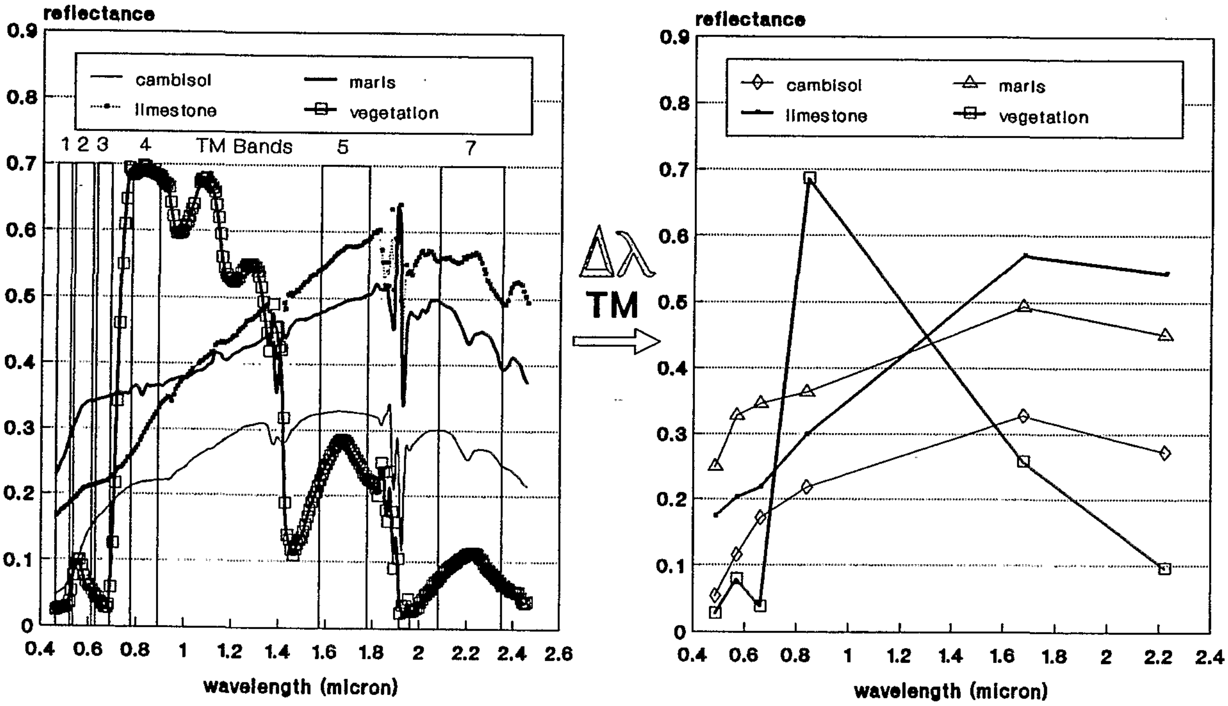


Fig. 6. Reflectance spectra of major substrate types (cambisols, marls and limestone) and photosynthetically active green vegetation in the spectral resolution of the field spectroradiometer (GER SIRIS) and the Landsat Thematic Mapper (Hill, 1992).

Satellite mapping of soil degradation and erosion hazards

The thematic analysis of the satellite images involved three separate stages. Fundamental pre-processing steps (radiometric and geometric corrections) were followed by a spectral decomposition of the original image spectra (spectral mixture modelling). After disturbing effects of terrain illumination and partial vegetation were compensated through renormalization techniques, various soil development classes were successfully mapped with a euclidian minimum distance classifier.

Radiometric and geometric pre-processing

The integration of spectroradiometric measurements into the analysis of optical data requires a conversion of the satellite images to physical quantities, such as reflectance factors. We have used an atmospheric correction method which is based on the formulation of radiative transfer as developed by Tanré *et al.* (1990). The method can be applied without contemporaneous atmospheric measurements since key parameters (aerosol optical depth) are inferred from scene-based estimates over dark targets. The radiometrically corrected scenes have then been geocoded by applying affine transformations. In order to improve local registration accuracy by a compensation of relief-dependent image distortions digital elevation data have been integrated to the correction process (Hill and Kohl, 1988), providing a final multi-temporal registration accuracy of approximately 15 meter (0.5 pixel).

Spectral mixture analysis

The method of computationally decomposing spectra into their proportions of spectral prototypes ("endmembers") has become known under the term "spectral mixture analysis" (Adams *et al.*, 1986; Boardman, 1989; Smith *et al.*, 1990).

Spectral mixture analysis assumes that most of the spectral variation in multi-spectral images is caused by mixtures of a limited number of surface materials (i.e. vegetation, soil, shade), and that these components have different reflectance spectra (Smith *et al.*, 1990). They commonly mix at the sub-pixel scale, producing mixed-pixel spectra. As a first approximation, spectral mixing may be modelled as a linear combination of pure component ("endmember") spectra, such that

$$R_i = \sum_{j=1}^{n} F_j \cdot RE_{ij} + \varepsilon_i$$

and

$$\sum_{j=1}^{n} F_j = 1 \qquad (1)$$

where R_i is the reflectance of the mixed spectrum in band i, RE_{ij} is reflectance of the *endmember* spectrum j in band i; F_j denotes the fraction of *endmember* j, and e_i the residual error in band i. A unique solution is possible as long as the number of spectral components does not exceed the number of bands plus one.

Linear mixing assumes that the surface components are large and/or opaque enough to allow photons to interact with only one component. Spectra can then be unmixed by inverting the linear mixing equation (equ. 1) using a least squares regression, while constraining the sum of the fractions to one. The objective is to isolate the spectral contributions of important surface materials ("endmember abundance's") before these are edited and recombined to produce thematic maps (Adams *et al.*, 1989).

Reference spectra

The selection of reference spectra ("spectral endmembers") is greatly simplified by field observations. For this experiment, three substrate spectra (cambisol, marl and limestone) and a characteristic green vegetation spectrum were chosen from the library of high spectral resolution spectroradiometric measurements from the study site (Altherr *et al.*, 1991), and then convolved to match the TM reflective bands (Table 1, Fig. 6). It was assumed that the surface reflectance of well-developed soils will, to a large extent, be modelled by the cambisol spectrum (EM2), while eroded surfaces would be characterised through increasing fractions of the parent rock spectra (EM3 and EM4).

Table 1. Reflectance factors of the used reference spectra (*endmember*)(Hill, 1992).

TM1	TM2	TM3	TM4	TM5	TM7	"endmember"	
0.052	0.081	0.044	0.584	0.236	0.085	Green vegetation	EM 1
0.077	0.159	0.210	0.269	0.388	0.329	Cambisol	EM 2
0.247	0.313	0.335	0.357	0.451	0.405	Marls	EM 3
0.156	0.182	0.195	0.268	0.513	0.489	Limestone	EM 4
0	0	0	0	0	0	"Shade"	EM 5

The green vegetation spectrum (EM1) accounts for varying amounts of sparse vegetation cover, and an additional spectral *endmember* (EM5: "shade") is required to isolate the influence of shading and shadows which relate to vegetation and soil/rock roughness elements, topography and solar elevation. "Shade" can mix with each of the other *endmembers* or with their mixtures, thereby modelling the spectrum of the *endmember* material when it is not fully illuminated (Adams *et al.*, 1989).

Spectral unmixing and renormalization

The four atmospherically corrected Thematic Mapper scenes were spectrally unmixed with the component matrix described above, producing a sequence of five fraction images for each date. Further processing involved selective editing of these fraction images.

In a first renormalisation process the fraction of shade (F_5) was deleted by rescaling the remaining fractions with the normalisation factor

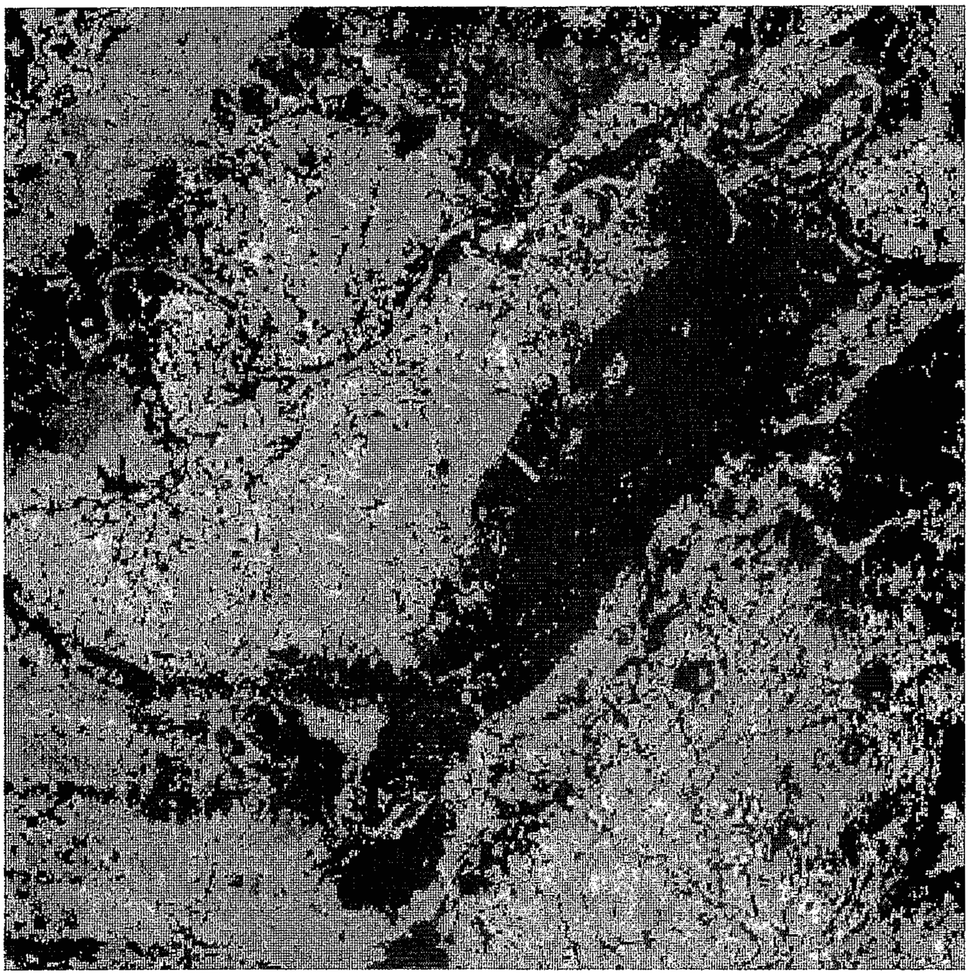
$$f = 1 \,/\, (1 - F_{shade}) \tag{2}$$

so that they sum again to unity

$$\sum_{j=1}^{n-1} F_j \cdot f = 1 \tag{3}$$

For example, a pixel having 0.33 vegetation, 0.33 soils (EM2 - EM4) and 0.33 shade would convert to 0.5 vegetation and 0.5 soils (Adams *et al.*, 1989). We have thus eliminated the disturbing influence of illumination and variable soil moisture, and retained that part of the signal which purely relates to vegetation and soil reflectance.

An additional selective renormalisation accordingly removed the fraction of green vegetation, but only for those pixels that had a vegetation fraction of less than 0.4. All other pixels have been blanked, assuming that the masking effect of green vegetation would increasingly devaluate an enhancement of soil-related spectral information. For all remaining pixels, however, the rescaled substrate fractions (EM2 - EM4) emphasise the relative proportions of developed soils and parent rock material. This processing method has been applied to each of the available Thematic Mapper scenes, and the resulting images were combined by averaging the *endmember* fractions for each pixel, thus providing a maximised area coverage (Fig. 7).



Each coloured pixel represents averaged fractions according to the number of scenes (at maximum four) that provided substrate-related information. Areas of permanent vegetation cover (Fr(EM1) > 0.4) are masked in black.

Fig. 7. Colour composite of renormalised fractions of the substrate *endmembers* (EM2 - EM4) used to spectrally unmix the Landsat Thematic Mapper images of the Ardèche study site (Hill, 1992).

Automatic mapping of soil degradation and erosion hazards

A map of soil development levels and erosion hazards was then obtained through a combination of cluster analysis and automatic classification of the renormalised fraction images.

Firstly, characteristic spectral mixing patterns were identified by applying the "k-means" unsupervised clustering method (Anderberg, 1973) to representative areas of the averaged fraction image. It was possible to define eleven substrate classes which, according to their relative proportions of *endmembers* EM2, EM3 and EM4, were associated to four soil degradation levels. The estimated abundance of *endmember* 2 (cambisol) and the sum of *endmember* fractions 3 and 4 seem strongly related to the intensity of pedogenetic processes, while relative proportions of the latter appear more sensitive to variations of the parent rock (Table 2).

Table 2. Correspondence of spectral mixing patterns, soil development levels and soil types (mixing proportions in percent)(Hill, 1992).

Class	EM 2 Cambisol	EM 3 Marls	EM4 Limestone	Soil development levels	Soil types (acc. to FAO, 1988)	Level
1 2 3	86.5 65.4 69.2	19.4 22.9 48.7	-5.8 11.7 -10.8	fair to satisfactory	Cambisols, Fluvisols Orthic Rendzinas and Calcaric Regosols	I
4 5	58.6 49.7	5.8 11.4	35.9 39.9	degraded	Calcaric Regosols and Renzic Leptosols	II
6 7 8	45.8 36.3 30.6	48.1 47.3 18.0	6.1 16.4 51.4	severely degraded	Rendzic, Eutric and Lithic Leptosols	III
9 10 11	21.0 11.2 11.2	89.2 34.4 16.3	-9.7 53.9 72.5	denuded	Marls Limestone Limestone	IV

It should be recalled that it is hardly possible to identify a direct correspondence between spectral mixture classes and individual soil types, unless pedogenetic characteristics are significantly correlated with spectral surface features (i.e. separation between level 2 and two first level 3 classes). But it appears feasible to establish a relation between soil development levels and groups of soil types (Table 2). Known characteristics of these soil types (i.e. Commission of the European Communities, 1985) can then serve the user to associate more quantitative descriptions with the spectral mixing classes, which in turn may help to apply the mapping results in the context of land management programmes.

The thematic map (Fig. 8) was obtained by applying a simple classification method (euclidian minimum distance) to the averaged substrate fraction image. Each pixel was assigned to that soil development class which most closely resembled its vector of mixing fractions.

The resulting map of soil development types is found in very good correspondence to the local patterns of soil degradation. As an extension of the thematic mapping approach, a combined soil erosion risk and hazard map is derived by reassigning soil development classes to major levels of erosion hazard (Table 3). Thanks to the outstanding geometric quality of Thematic Mapper imagery, the satellite-derived maps can be overlaid on topographic information up to a scale of 1:50,000 (Fig. 8). Because of their high spatial resolution (30x30 meter pixels), they both appear particularly suited to complement existing large-scale mapping of erosion risk in Mediterranean areas as it is developed in the CORINE programme (Bonfils, 1989; Giordano, 1990).

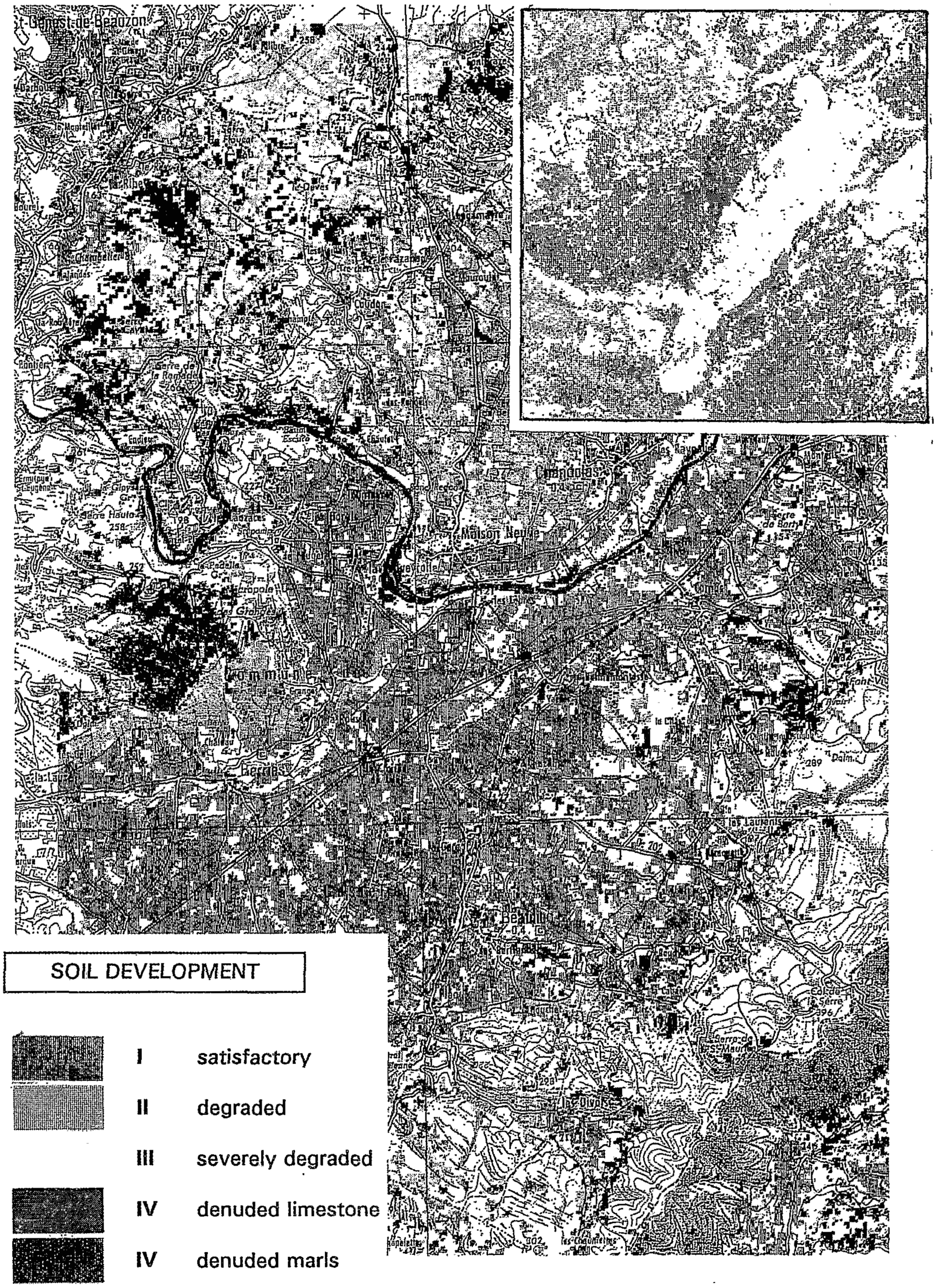


Fig. 8. Automatic mapping of soil development levels in the Ardèche test site, superimposed on "Carte Topographique 1:50,000, Feuille Bessèges" (here represented in scale 1:60,000). A derived map of low (brown), medium (ochre) and severe erosion hazards (red) is inserted to the upper right. Note that unmapped areas (white) are permanently covered by vegetation, indicating low erosion risk.

Table 3. Assignment of soil development classes and erosion hazards (Hill, 1992).

Soil development classes	Soil types	Erosion hazard
1 - 3	Cambisols, Calcaric Fluvisols, Orthic Rendzinas and Calcaric Regosols	Low
4 - 6	Regosols, Rendzic and Eutric Leptosols	High
7 - 11	Lithic Leptosols and Outcropping Parent Rock	Very high

Mapping accuracy

Thematic mapping accuracy was assessed through comparisons with aerial photographs, detailed maps of degraded vegetation (Pollicini, 1991) and results from a pedological field survey (Riezebos *et al.*, 1990).

The comparison of satellite-mapped soil development types and degraded vegetation communities ("garrigue"-shrubs and rangelands) was considered important for two reasons. The overall proportion of classes 5 - 11 should be close to 100 % since these areas are almost exclusively associated with severely degraded soils (mainly leptosols) or outcropping parent rock (Pollicini, 1991). Given the structure of *garrigue* and rangeland vegetation (low shrubs and grass patches, often separated by exposed bare soil or rock), a good agreement would also confirm the method's ability to successfully compensate for varying amounts of sparse vegetation cover.

Both aspects appear well confirmed since more than 85% of the surface have been classified as areas of degraded or even severely degraded soils and largely exposed rock (Table 4). The validity of the unmixing approach is additionally supported by the class differentiation itself: groups III and IV are dominated by categories which emphasise spectral characteristics of marls (6, 7 and 9), while classes with high proportions of the limestone spectrum (8, 10 and 11) are almost completely absent. In fact, the reference areas are almost completely located on cretaceous marls.

An additional confirmation of the mapping results is obtained from the direct comparison to 31 soil profile descriptions from Riezebos *et al.* (1990) which, according to some important criteria (i.e. soil type, profile depth, proportion of parent rock exposed at the surface), were associated to the four soil development levels of Table 2. The geographic coordinates of the field records served to precisely relocate these pedologic "control points" on the geocoded satellite map, so that an error matrix could be computed. Taking into account that some bias might be introduced by comparing local field observations (profiles) to a 30x30 meter pixel raster with an average geometric location accuracy of 15 meter, the resulting precision (weighted average of 74.2 %) is considered exceptionally good (Table 5). There is no confusion between levels I and IV, and the separation between levels I/II and levels III/IV is also satisfactory. Most mapping errors occur between level II and III, but the respective soil types (regosols and various leptosols) can't be consistently separated even in the field referring only to soil surface conditions.

Comparisons to available air photos additionally confirm that the mapping results do well compare with the spatial patterns of well-developed and degraded soils in the study site. The satellite-based map even maintains high precision in areas where different soils are found within the same lithological unit. But it should be noted that more advanced pattern recognition algorithms, such as neural networks (Kanellopoulos *et al.*, 1992), may improve these good mapping results.

Table 4. Ardèche study site: proportions (per cent) of satellite-mapped substrate classes within the field-mapped areas of degraded vegetation (= 100 %)(Hill, 1992).

Class	1	2	3	4	5	6	7	8	9	10	11
%	0.9	7.7	5.0	0.6	5.2	26.6	38.7	0.5	13.6	0	1.2
%	13.6			5.8		65.8			14.8		
Level	I			II		III			IV		

Table 5. Soil development levels in the comparison of pedological field campaigns and the satellite based mapping approach (error matrix)(Hill, 1992).

Classification	Pedological field campaign (31 profiles)				
	I	II	III	IV	
I	7	1	0	0	
II	2	5	3	0	
III	0	1	6	1	
IV	0	0	0	5	
Total	9	7	9	6	
% correct	77.8	71.4	66.7	83.3	Av: 74.2

Portability and general applicability of the method

As a first extension of this detailed pilot study, the method was successfully applied on a larger regional scale (2,500 square kilometres) where lithologic and environmental conditions remained almost identical to the primary test site (the so-called "Bas Vivarais" area). However, an essential requirement for more general applicability is that the method can be transferred to locations with a wider range of lithologic conditions without changing too many of the processing parameters. It is therefore intended to conduct a number of additional verification experiments on different locations in the Mediterranean basin.

A first study has been initiated in Greece (Peloponnesos peninsula), where the method was applied with identical (!) processing parameters (i.e. *spectral endmembers*) as in southern France. The preliminary results appear quite promising (Fig. 9). Again, well-developed and degraded soils but also outcropping parent rock (evidence of most severe erosion hazards) were identified, though rock types are partially different from those in the Ardèche site. This might imply that the *spectral endmembers* (in TM spectral resolution) might represent more general rather than individual bedrock characteristics (in the sense that the marl and limestone spectra serve as prototypes for freshly eroded/unweathered and weathered rock surfaces). However, more detailed investigations are required to confirm these trends.

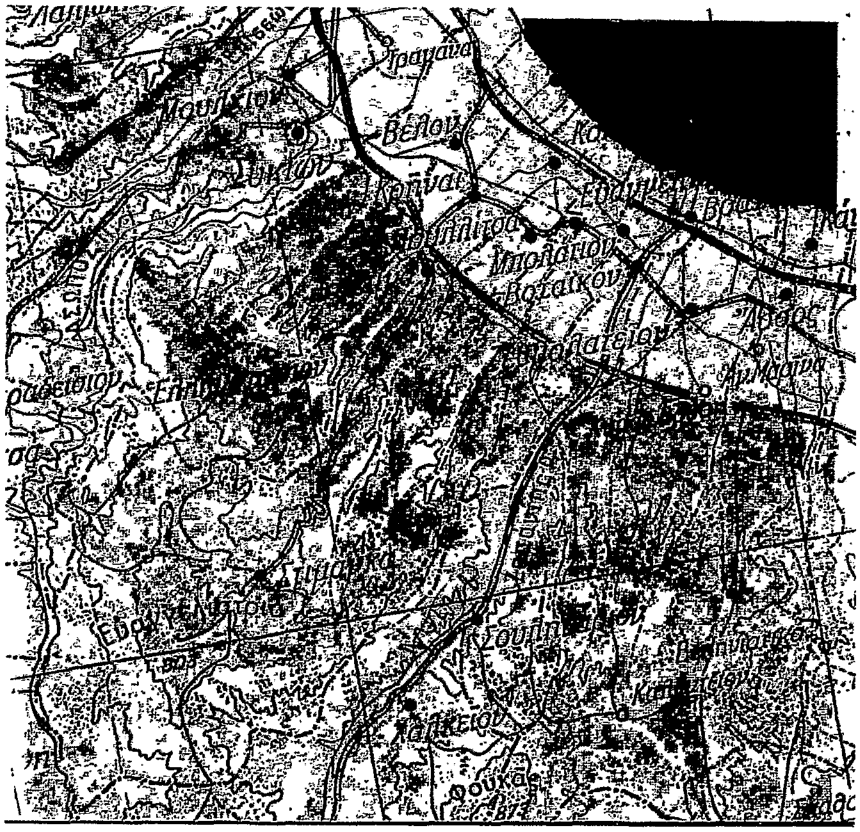


Fig. 9. Satellite-based mapping (Landsat-5 Thematic Mapper from May 19, 1985) of soil development classes and erosion hazards west of the town of Korinthos (northern Peloponnesos, Greece), overlaid on the topographical map 1:200,000 (here presented in scale 1:120,000).

Additional tests are planned for two Spanish study sites (Valencia, Almeria) where required ground information is provided by institutes that already cooperate with the Joint Research Centre.

Conclusions

Soil maps divide the landscape into discrete soil mapping units with distinct boundaries. Although the delineation of mapping units is useful for descriptive purposes, abrupt soil boundaries are rare due to the nature of soil-forming processes. More often, a gradual transition in soil properties and profiles occur over the landscape. This variation is amenable to observation from remote platforms, which can afford a synoptic perspective of a geographic area. Remotely acquired images show variations in surface reflectance, which can indicate corresponding variations in the underlying soil profiles. However, despite the demonstrated utility of advanced remote sensing techniques for pedologic studies, neither Landsat data nor data from other satellite sensors have so far been *routinely* used for soil mapping applications.

Results of this pilot study confirm that regional patterns of soil degradation and erosion hazards can be reliably mapped with optical imagery from operational earth observation satellites, such as the Landsat platforms with their Thematic Mapper sensor. However, the method we have presented is limited to conditions where soil degradation is significantly correlated with spectrally detectable surface characteristics, and where green vegetation cover is not too dense. This seems valid for large areas of the Mediterranean basin.

The approach, which is primarily based on linear spectral mixture analysis, provides results at a level of precision and spatial differentiation which, due to methodological and financial constraints, can't be obtained through conventional mapping approaches. It is again to be emphasised that spectral mixture analysis interprets optical images in the context of physically-validated constraints, since the data analysis is directly controlled by spectroradiometric field and laboratory measurements. The method then requires radiometric corrections of the satellite images prior to the thematic analysis of the data sets but, once these corrections are applied, also holds the potential to be largely standardised in terms of the required processing parameters (i.e. *spectral endmembers*). The outstanding geometric properties of the Thematic Mapper images facilitate an integration of satellite-derived mapping and topographic data bases up to a scale of 1:50,000. This, in conjunction with the continued availability of earth observation data from the Landsat Thematic Mappers (Landsat-6 to be launched in January 1993), suggests that the method might also be applied for regular soil degradation monitoring.

It is concluded that this approach holds some potential to be finally applied *routinely*, and it thus appears particularly suited to complement available large-scale surveys of soil erosion risks by providing detailed inventories of the *existing* soil degradation processes and erosion hazards. However, further verification experiments under variable environmental conditions are still required to draw a final conclusion on its future operational applicability. Some of these studies have already been initiated. If the results confirm the conclusions which can be drawn from this pilot study, the method might become a substantial element of regional land development programmes, and take a major role in Mediterranean land degradation analysis.

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