Annals of Arid Zone 40(2): 103-140, 2001

The Potential of Remote Sensing and GIS for Desertification Monitoring and Assessment

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Abstract: Remote sensing based data are a valuable source for extracting spatially and temporally explicit information to monitor and assess regions threatened by desertification processes. Additional value can often be added through integrating remote sensing derived information with auxiliary data through a geoinformatics approach. This paper first addresses the essential problem of implementing relevant conceptual frameworks, of identifying processes, and of developing process dependant indicators. Data processing has therefore to focus on prerequisites ensuring the optimum identification and quantification of such indicators. A number of case studies is presented to explicate the significance of quantitative indicator based concepts. Moreover, the importance of integrating socio-economic boundary conditions and anthropogenic influences is outlined. Finally, the perspectives of future developments and their likely implications for remote sensing and Geographical Information Systems (GIS) based desertification research are summarized.

Key words: Remote sesning, GIS, desertification, land degradation, monitoring.

The last decades have seen numerous political decisions with relevance for desertification research, such as the call for sustainable development issued at the UN Conference on Environment and Development (Halpern, 1992), or the explicit recognition of the threat to human welfare through processes of desertification as expressed in the United Nations Convention to Combat Desertification (UNCCD, 1994). In this context, it has also been emphasized that research should support policy makers and administrative authorities dedicated to establishing locally adapted schemes for sustainable land management.

As a first step in this process, it is mandatory to provide the stakeholders with a sound assessment of present resources and, if possible, the temporal development thereof. This objective cannot be met by conventional approaches alone, which commonly rely on field-based mapping of ecological parameters, providing a high level of detail, but only limited spatial coverage. Rather, information is needed for larger landscape units, e.g., through integrating field, based approaches with remote sensing techniques. Methodologies based on remote sensing data take advantage of a synoptic, repetitive and consistent perspective over large areas. Combined with the functionality of today's generation of GIS, such strategies provide a powerful tool for monitoring and assessing areas under the threat of desertification.

Advanced methodologies for desertification monitoring and assessment are needed, indeed. While our knowledge about desertification processes and potential anthropogenic causes is steadily growing (Mainguet, 1994; Mainguet, 1999; Thornes, 1999; van der Leeuw, 1999), we are often lacking accurate figures to assess the actual environmental threats. Accordingly, the same applies to subsequent considerations on adequate countermeasures to ensure sustainability. Despite the fact that methods for large scale assessments are widely employed and well developed, a monitoring of desertification processes at appropriate spatial and temporal scales and with adequate methodologies from remote sensing data is still an issue. This problem is well documented in numerous publications discussing the severity of desertification impacts from regional to global scale (Binns, 1990; Hellden, 1991; Thomas and Middleton, 1994; Hill *et al.*, 1998). Accordingly, desertification impact assessments ask for a thorough quantification of indicators in the context of global change research, as desertification processes inherently feedback into the integral development of many terrestrial ecosystems (Walker *et al.*, 1999).

In the course of this paper, studies and examples are given from sub-humid, semi-arid and arid regions around the Mediterranean Sea. Nevertheless, most of the problems associated with these cases are common to other ecosystems and other regions of the world. Hence, the main objective is to develop a framework that can serve as a kind of philosophy on what we believe is essential for desertification monitoring and assessment with remote sensing data.

Concepts Relevant to Desertification Monitoring

A weakness of many approaches analyzing desertification related processes is the lack of a conceptual framework, defining why desertification-monitoring should be tackled in a certain way and how related problems could be solved. This not only includes a proper description of the respective threats, but also a definition of systematic pathways on how these problems can be approached methodologically (Hill *et al.*, 1995a). On one hand, remote sensing data play an important role as one of the major sources of up-to-date and physically based information. On the other hand, GIS delivers the toolbox that enables data integration, analysis, and information extraction. In the following, we will develop such a conceptual framework, discuss the respective remote sensing based options and outline the potential benefits of integrating data sources from remote sensing with GIS based methods.

Processes, indicators and scale

In order to understand how remote sensing and GIS may support the evaluation of desertification threats for different ecosystems, we first need to understand the environmental setting of these systems. Only a precise knowledge about governing processes leads to monitoring options and to meaningful conclusions on how to combat the respective threats. There have been numerous approaches to conceptualize a chain from triggering processes to potential effects. Here, we develop a concept on how to derive useful indicators for desertification monitoring on the basis of examples from the European Mediterranean.

A first and simplified approach may concentrate on geological/geomorphological, climatic, and anthropogenic factors and their interrelationships (Fig. 1). It is evident that most processes relevant to desertification risk

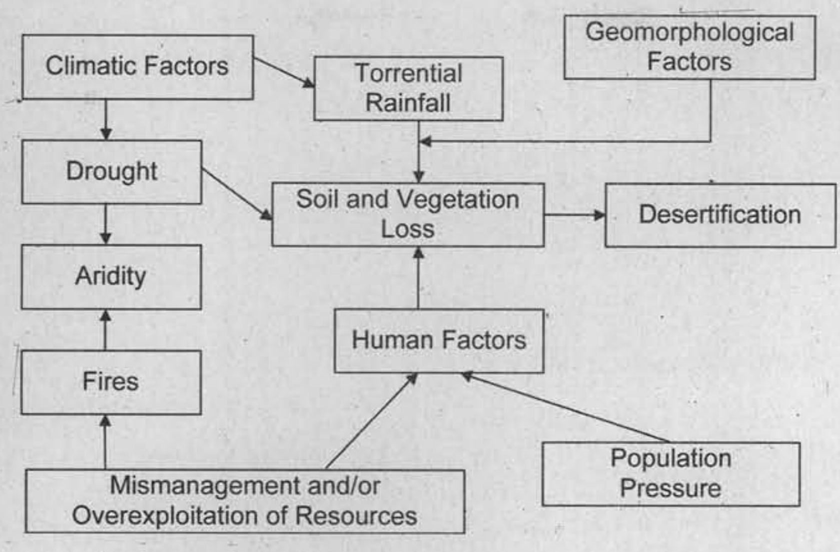

Fig. 1. Factors leading to desertification (from Perez-Trejo, 1994).

assessment depend upon factors determining changes in soil or vegetation properties. While we have to understand the logical chain of determinants, we have also to derive pathways on how to conclude from those processes on relevant indicators.

To ultimately assess which processes are relevant in a particular region, we have to consider the individual setting in more detail (Fig. 2). This may, for example, include that ecosystems in different elevation zones lead to different desertification processes under similar pressure, that processes can only be reversed up to a certain threshold of change, or that effects of degradation depend upon the respective plant community (which is not necessarily detectable through remote sensing). In general, a critical assessment of environmental boundary conditions will always build the mandatory basis for a serious assessment of desertification threats.

Once potential processes and their consequences are understood, it is possible to evaluate indicators, which can be regarded as expression of these consequences. A wide variety of indicator systems does exist today – most exhibit a rather theoretic background, some can be regarded as relevant for environmental assessments, and only a few bear the potential to serve as input for remote-sensing-driven monitoring approaches. A common classification scheme is illustrated through the Pressure-State-Response (PSR) model that tries to conceptualize different classes of indicators. Pressure indicators describe processes responsible for initializing changes, state indicators describe the corresponding system state or its modification, and response indicators express the consequences – including socio-economic and political ones – from such changes. Remote sensing based monitoring will usually concentrate on assessing the state of the environment. It is hence the source – and often the only reliable source – upon which decisions concerning countermeasures against desertification can be based.

In this context, it is crucial to reflect upon the problem of scale: indicators are always embedded in the continua of time and space (Woodcock and Strahler, 1987; Imeson, 1996). Such considerations lead to tangible consequences for remote sensing based monitoring concepts, as appropriate strategies will always be based on adequate sensor characteristics (Fig. 3).

Remote sensing concepts

Today, we encounter a wide range of remote sensing systems: classical aerial photographs are still employed for numerous applications all over the world, while many digital airborne systems reach operational status. Satellite-based platforms acquire massive amounts of digital data every day and among hundreds of active satellites many deliver earth observation data of various kinds.

In the following we will concentrate on those remote sensing concepts, which are most widely used for desertification monitoring and assessment, or which are likely to have a great potential in the future. In most cases, optical remote sensing data observing the earth in wavelength regions between 400 and 2500 nm are employed, i.e., data covering the visible to the shortwave-infrared domain. Even when concentrating on this kind of sensors, there are still ample concepts around and as many to be developed in the near future (Fig. 4).

Three sensor-related categories shall illustrate the potential pathways relevant to desertification monitoring concepts, notwithstanding various other categorisations:

- aerial vs. satellite based imagery,
- TM-like satellite sensors vs. others, and
- classical vs. hyperspectral data.

The first remote sensing concepts were based on aerial photographs acquired from different kinds of platforms. Today, numerous applications are still relying on aerial photographs, illustrating the unbroken value

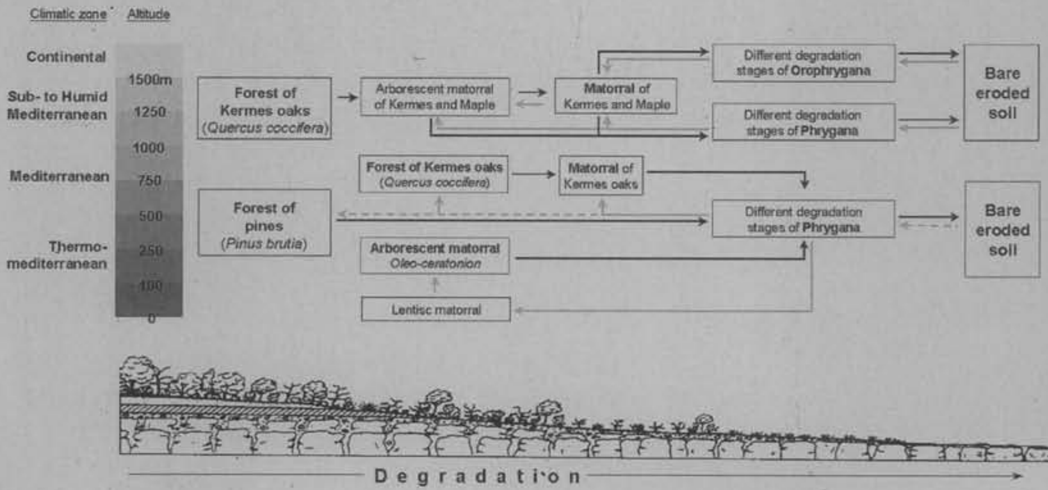

Fig. 2. Potential states of grazing-induced desertification on Crete, Greece (modified after Tsiourlis et al., 1998).

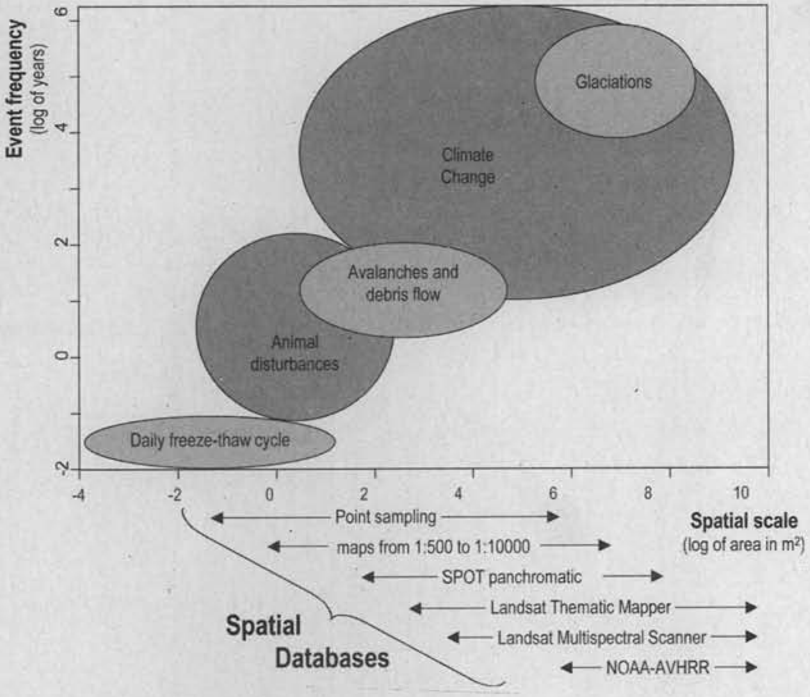

Fig. 3. Spatio-temporal processes, scale, and monitoring approaches (modified after Duguay and Walker, 1996).

of this data source. The advantages are obvious: Data may be acquired with great flexibility for specified targets at different scales; diverse films, filters, and cameras can be combined to ensure optimum results; data analysis features a broad range of alternatives, including techniques from field based mapping to digital image interpretation. Besides, there are established ways of photogrammetric image analysis and stereo-interpretation.

However, there are also considerable drawbacks. A flight campaign is labor and time intensive, results may not exactly be comparable in multitemporal approaches, and film material is limited in its sensitivity between the visible and near-infrared wavelength regions. Some of these shortcomings can be overcome by modern technology such as digital airborne systems. Nevertheless, limited area coverage and rather high acquisition costs are two factors inherent to any kind of airborne sensors.

With a history of about 30 years, operational earth observation satellites are an established alternative to aerial photographs (Graetz, 1996; Goward and Masek, 2001). An exceptional role play

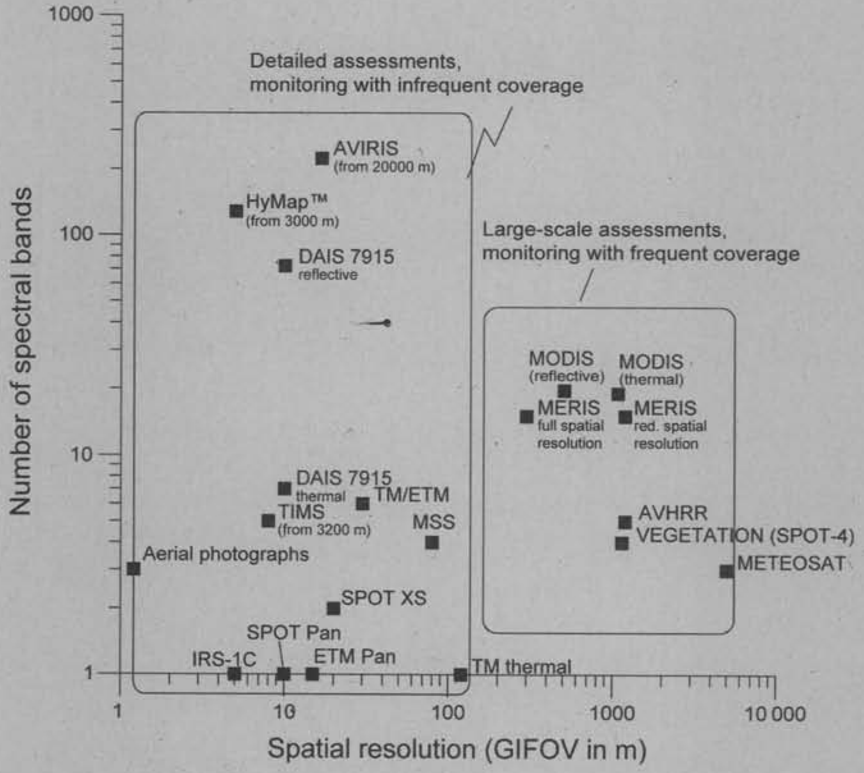

Fig. 4. Spectral and spatial resolution of important operational, planned, and experimental remote sensing systems (from Hill, 2000).

Landsat-like systems, developed from the early concepts of ERTS-1 that became operational in 1972[1]. A consistent sensor philosophy ranging from the early Multispectral Scanner (MSS), over the Thematic Mapper (TM) to the latest Enhanced Thematic Mapper generation (ETM+) ensures data consistency beyond other satellite systems (Table 1). There are also ongoing efforts to develop an advanced sensor generation merging benefits from TM and other systems with recent technological improvements[2]. Similar imagery is delivered by the Système Probatoire d'Observation de la Terre (SPOT) or the Indian Remote Sensing Satellite (IRS). However, these systems have drawbacks relating to radiometric calibration, spectral resolution, and particularly the considerably shorter time span since their first launch.

The only alternative with acquisition records back to late seventies is the Advanced Very High Resolution Radiometer (AVHRR). However, data from this sensor lack an

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[1] ERTS: Earth Resources Technology Satellite; the platform was renamed to "Landsat" after the successful launch of the second MSS sensor onboard of ERTS-2 in 1975.

[2] The Advanced Land Imager (ALI) onboard the first Earth Observing mission platform (EO-1) is an experimental Landsat-like system with advanced sensor configuration.

Table 1. Characteristics of operational sensors from different Landsat generations (USGS, 1979; Markham and Barker, 1983; USGS and NOAA, 1984; Mika, 1997)

	MSS	TM	ETM+
Number of bands*	4	7	8
Mean spectral sensitivity (nm)**	1: 500-600	1: 450-520	1: 450-515
	2: 600-700	2: 520-600	2: 525-605
	3: 700-800	3: 630-690	3: 630-690
	4: 800-1100	4: 760-900	4: 750-900
		5: 1550-1750	5: 1550-1750
		6: 10400-12500	6: 10400-12500
		7: 2080-2350	7: 2090-2350
			Pan: 520-900
Geometric resolution (m^2)	79 x 79	30 x 30	30 x 30
		(band 6: 120 x 120)	(band 6: 60 x 60, Pan: 15 x 15)
Radiometric resolution (bit)	7	8	8
Repetition rate (days)	18 (Landsat 1-3)	16	16
	16 (Landsat 4 and 5)		
Coverage/scene (km^2)	185 x 185	185 x 172	183 x 170
Lifetime***	1972 - 1992	Since 1983	Since 1999

* for MSS only bands featured at all missions are counted.

** MSS bands are named 4, 5, 6, and 7 for Landsat 1-3; Landsat 3 also featured a thermal band 8.

***lifetime is given as cumulated acquisition time of all Landsat platforms featuring the respective sensor; MSS data acquisition on Landsat-5 was suspended while the platform and its TM sensor are still operational.

adequate spectral and – more important – geometric resolution. While global coverage and high repeat rates are strong arguments for such a system, it is not possible to seriously monitor landscape-scale processes or indicators with a geometric resolution of 1 km or less (Hill *et al*., 1995c; Graetz, 1996).

Data from Landsat are available for all regions of the world and archives from various receiving stations feature extensive multi-temporal datasets for most areas of interest. The ideal combination of high geometric resolution, a repetition rate of almost twice per month and spectral bands in the important wavelength regions from visible over near-infrared to shortwave-infrared are key factors for the system's continuous employment. A wealth of applications is based on data from Landsat, of which desertification monitoring is gaining importance. The rationale behind this is that desertification – in opposition to many other landscape-relevant processes – is understood as a long-term phenomenon. Desertification is taking place over decades rather than days, weeks or months, thereby shifting the main interest in remote sensing applications from high repetition rates to continuous coverage over a long time span.

However, even with a rather good spectral resolution compared to other earth observation systems, today's Landsat sensor generation is limited when relevant features can only be identified with extremely high spectral resolution. This applies to all surface elements only detectable in narrow wavelength regions, like many minerals generating distinct absorption bands. Furthermore, many surface components exhibit only marginal spectral differences from others (e.g., dead standing plant material compared to many soils). This is the domain of hyperspectral remote sensing systems.

The term "hyperspectral data" is usually used when tens, hundreds or even thousands of narrow spectral bands form a more or less continuous spectrum (Fig. 5). Technical problems, for example due to the small amount of energy available in such distinct bands, diminish with advancing sensor technology. Plans for satellite-based hyperspectral systems are well advanced today and experimental sensors already launched. Many sensors for field and laboratory applications or systems mounted on aircrafts are operational or semi-operational. In the near future, we will hopefully see different hyperspectral satellite systems that will enable new applications in desertification monitoring, solve some of the problems of repetitive spectral analysis, and build a basis for modelling approaches that will otherwise lack input data of sufficient quality and accuracy.

Remote sensing, GIS, and modelling

It would probably be most adequate, not to distinguish at all between systems for remote sensing data analysis on one hand and GIS on the other. Yet, while many concepts of remote sensing data analysis and consequently many features of digital image processing systems are common to GIS, the latter one is often misunderstood as a system exclusively dealing with vector data. A division in those two branches is rather a historically grown consequence of different scientific communities or diverse technical issues driving the respective developments. Today, the separation is rather due to technical shortcomings of the individual systems in the market or to knowledge deficits of the most important component in such systems – the human factor.

Here, the attention shall be drawn towards the ongoing integration of these components. There is an obvious trend in system design to incorporate as much functionality as possible from vector and raster data handling capabilities as well as from spatial analysis methods for both domains. The importance of this integration process has been recognized earlier and it has been emphasized that it is one of the prerequisites for effective and operational spatial information retrieval (Wilkinson, 1996; Star *et al.*, 1997; Hostert, 1999).

Integration is not a one-way process. It is obvious that remote sensing data play a principal role in generating up-to-date information in a GIS-environment. For example, land use or land cover updates can be derived from multitemporal remote sensing data on a regular basis. At the same time, incorporating diverse data sources in a common environment largely expands analysis options for remote sensing data beyond the limits of spectral feature identification. Knowledge and context based classification or analysis schemes enable the separation of features with ambiguous spectral characteristics.

An important option is to stratify heterogeneous landscapes into rather

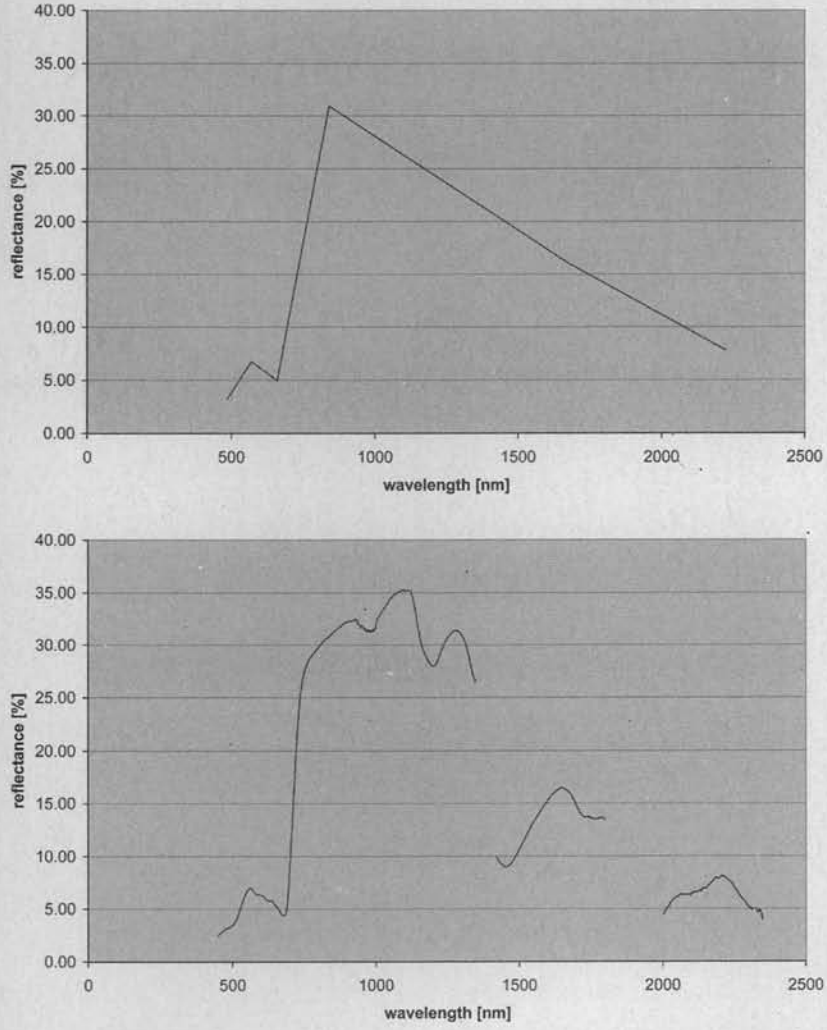

Fig. 5. Spectral characterisation of vegetation in discontinuous bands of Landsat TM (top) compared to hyperspectral measurements from ASD FieldSpec-II (bottom); missing wavelength regions in the hyperspectral measurements result from water vapour absorption.

homogeneous units corresponding to specific features. The application of elaborated pre-stratification strategies permits individual data analysis schemes, as spectral variation due to certain landscape attributes can be ruled out in advance. For example, including knowledge about specific soils in a multi-temporal analysis may narrow down the reasons for spectral variation to yearly differences in dry biomass. Similarly,

Fig. 6. Integrating vegetation (top) and geology (below) to relate ground measurements (black lines) to features in a DEM or satellite data (bottom).

GIS-layers of vegetation units and geological strata can be used to relate hyperspectral measurements in the field to respective features in satellite imagery (Fig. 6).

Integrating spatialized information from various sources is also a prerequisite to run and develop sound modelling approaches. Models represent complex processes of the real world in a more or less simplified way. By such means, it is possible to process various scenarios and to predict potential influences and developments. Moreover, by modifying parameters in a prearranged scheme, we may test the sensitivity of different variables of a model to gain a deeper insight into the respective process chain. Therefore, modelling requires a rather deep understanding of the processes triggering a system and how such processes may be described or simplified adequately.

Remote sensing driven modelling offers a wide range of promising opportunities for desertification assessment studies and may be classified into quite as many categories. We can, for example, consider how processes are modelled from a methodological point of view, categorize on the basis of driving parameters or output information, or classify models after their scaling properties (De Roo, 1993; Kirkby *et al.*, 1996; Legg *et al.*, 1998). In the context of this paper, a thematic standpoint may be most appropriate. Important spatialized approaches include soil erosion models (e.g., De Jong, 1994), hydrological models (e.g., Boer, 1999), models on vegetation dynamics (e.g., Legg *et al.*, 1998), or – more generally speaking – models of energy and matter fluxes in one or between different ecosystems. Likewise, there are often combined approaches reflecting inherently linked system components or processes, like for example hydrological surface runoff models for soil erosion assessments (De Roo and Riezebos, 1992; Boer, 1999).

Focussing on spatialized models for desertification or land degradation assessments, remote sensing plays an important role for creating continuous input information at various spatial and temporal scales (De Jong, 1994; Boer, 1999; Tabarant, 1999). In addition, models can be iteratively re-calibrated with up-to-date remote sensing based information on the actual state of the environment.

The most sophisticated way to handle such data, to run and calibrate models, and to present and analyze output information, is to integrate all components within a GIS environment (Fedra, 1996). It should be noted that technical details on how to implement a model can usually be adequately solved in different ways. However, ecological modelling for desertification studies is often far from being operational in a sense that models are not transferable to other environmental settings. In the future, this research area will probably gain most from modifying modelling approaches in such a way that desertification issues in different regions of the world may be satisfactorily assessed with minor model adjustments.

Quantitative Assessments

Remote Sensing based methods have considerably advanced during the past decades. Early image processing techniques clearly focussed on qualitative data analysis, whereas more and more applications today employ quantitative methods. Qualitative results, e.g., digital image classifications, or semi-quantitative outputs, such as uncalibrated vegetation indices, will still play an important role in the future of desertification monitoring and assessment. Remote sensing based assessments in this context answer questions like: "What is happening?". However, quantitative measures of environmental variables, such as biomass or soil organic and inorganic carbon, are needed to answer questions like: "How severe are the changes we are facing and what might be adequate countermeasures?".

In many, if not in most cases, it is well known that processes leading to environmental degradation are taking place, but there is only limited knowledge on where exactly the threat is most severe. It is therefore mandatory to develop concepts providing reliable, reproducible and continuous information on desertification processes and their respective indicators. Different prerequisites have to be met to ensure meaningful quantitative assessments of desertification from remote sensing data:

- Processing has to remove atmospheric disturbances effectively, thereby enabling optimized identification of features and quantification of information.
- It must be ensured that such features are comparable between multi-temporal datasets.
- Remote sensing derived information needs to be integrated with ground based or other data bases. Consistency between multi-source datasets is therefore indispensable.

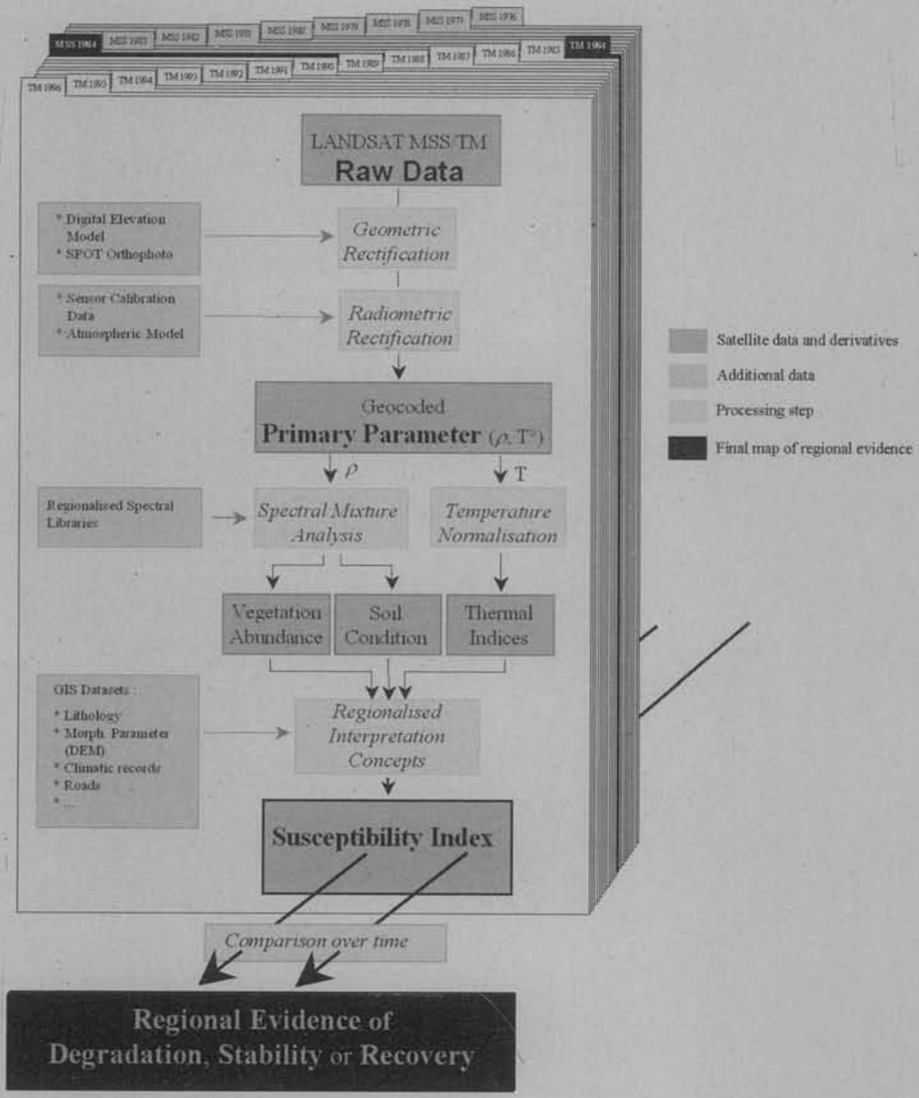

Fig. 7. Example of a two-level processing scheme for multi-temporal datasets.

A two-level concept may be employed to generate data fulfilling these prerequisites and to develop meaningful indicators describing processes relevant to desertification. In a first step, primary indicators based on standardized pre-processing schemes are derived from remote sensing data. Most remote sensing based assessments, including qualitative methods like image classification, will equally benefit in their accuracy from precise and standardized pre-processing techniques. Subsequently, state indicators or basic

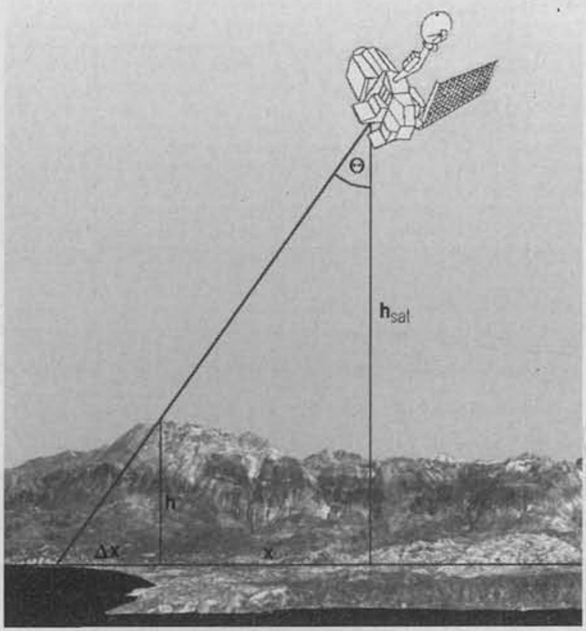

Fig. 8. Terrain-dependant geometric distortion in Landsat-like remote sensing data; h_{sat}*: satellite elevation, h: terrain element elevation,* θ*: scan angle, x: orthogonal pixel position,* Δx*: distorted pixel position.*

information for indicator development are extracted from the pre-processed data (Fig. 7).

From data to primary indicators

Pre-processing of remote sensing data has to be regarded as an integral element of image processing techniques. Essentially, geometric and radiometric pre-processing are the two important steps in this first part of the image processing chain. Usually, operational remote sensing data are delivered as system corrected data to the customer, i.e., data should be free of systematic and reproducible sensor specific errors. Apart from eventual inconsistencies due to non-systematic errors in image acquisition, transmission, or archiving facilities, raw data are not or not adequately registered to specific reference grids in most cases. Moreover, data are not corrected for radiometric distortions due to atmospheric and terrain-dependant influences.

A precise geocoding ensures consistency of multi-temporal data from a single sensor as well as the accurate integration of data from different sources for advanced analysis schemes. A specific problem concerning remote sensing data is their different viewing geometry compared to conventional mapping products, i.e., their non-orthogonal projection properties. Elevated surface features exhibit increasing radial distortions with growing elevations above the map reference level and growing nadir distance (Fig. 8). Accurate solutions therefore require a DEM-based correction procedure. Additionally, unstable image platforms, such as planes, may depart

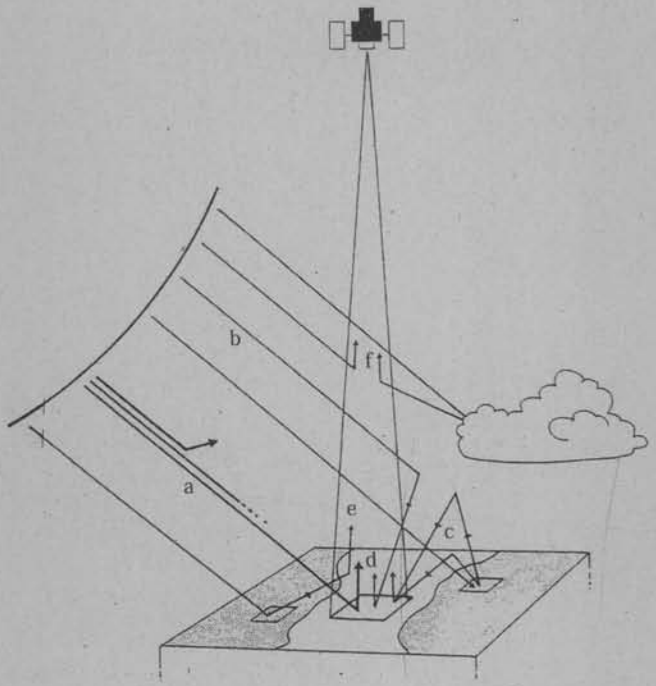

Fig. 9. Atmospheric influences in flat terrain; a: direct radiation, b: diffuse radiation, c: multiple scattering from surrounding, d: target reflectance, e: reflectance from surrounding, f: path radiance (modified after Tanré et al., 1986).

from the idealized image acquisition configuration (i.e., nadir view and no departure from the modelled flight path in any dimension). In such cases, parametric corrections and photogrammetric solutions are mandatory to create geometrically precise results.

A precise radiometric correction of image data is equally important for multi- temporal image analysis schemes. Otherwise, desertification indicators may for example represent variations in atmospheric conditions or sensor degradation rather than environmental change or stability. It is important to be aware of the fact that many state indicators can only be calculated on the basis of standardized primary indicators, such as surface reflectances or temperatures.

Three elements of radiometric pre-processing may be distinguished: sensor calibration, atmospheric correction, and illumination correction, of which the latter two are closely interrelated. Sensor calibration transfers uncalibrated digital numbers (DN) into meaningful physical units, like for example radiances. Calibration coefficients have therefore to be known, if previously uncalibrated data need to be processed. As sensor calibration is subject to changes over time, the respective time-dependent calibration coefficients should be employed (Teillet and Fedosejevs, 1995).

Atmospheric and illumination correction should be processed simultaneously, as the magnitude of topographically induced effects is partially governed by atmospheric properties. Absorption and scattering processes influence the amount of radiance received by a surface element. The same effects apply during the upward path of radiance towards the sensor (Fig. 9). Topography influences downward and upward fluxes from and to the earth's surface through multiple effects, such as the angular geometric configuration, the visible proportion of hemispherical sky for each surface element, or the topography-dependant part of received diffuse light.

Without further elaborating the physics and mathematical solutions to correct such effects, it shall be mentioned that the combined effects of atmospheric and topographic influences can be parameterized quite accurately by inverting the processes changing the signal on its way through the atmosphere. Such a parameterisation is for example available through the "Simulation of the Satellite Signal in the Solar Spectrum" (5S) as developed by Tanré *et al.* (1986, 1990) or its successor 6S (Vermote *et al.*, 1994, 1997). A professional solution can be derived by coupling the atmospheric correction model with a topographic illumination model (Itten *et al.*, 1992; Hill *et al.*, 1995b; Richter, 1997).

From primary indicators to state indicators

Primary indicators like spectral reflectances are physically meaningful and quantitatively comparable figures. Nevertheless, they usually lack a meaning for the assessment of desertification phenomena. It is therefore crucial to develop the concept one step further and to transfer physically meaningful data into thematic meaningful information. There are various pathways to do so and the approach actually chosen should solely depend on the indicators to be developed. Some indicators may base on rather simple prerequisites, for example changes in the percentage of certain land use classes, while others might represent highly integrated variables or even the result of complex models. With such a wide range of potential concepts just exemplary methods shall be introduced here. As classification schemes are widely applied and advantages as well as drawbacks are well documented elsewhere (e.g., Lillesand and Kiefer, 1999; Richards and Jia, 1999), we will focus on advantageous alternatives in the context of remote sensing based desertification assessment and monitoring.

One of the most useful and flexible methods in analysing multi- or hyperspectral imagery is spectral mixture analysis (SMA). Especially when image classification methods or uncalibrated measures do not extract valuable information from remote sensing data, SMA is one of the alternatives. In most cases heterogeneous surface properties produce mixed spectral signatures for properties we are interested in. These properties might be as diverse as the fraction of photosynthetic active vegetation or the organic matter content in soils.

SMA provides a physically based tool that enables a quantitative solution of such questions. Let us assume that only a few relevant components, so called "endmembers", explain a majority of the surface's spectral signal recorded at a sensor. If we are able to identify these endmembers and to define their spectral characteristics,

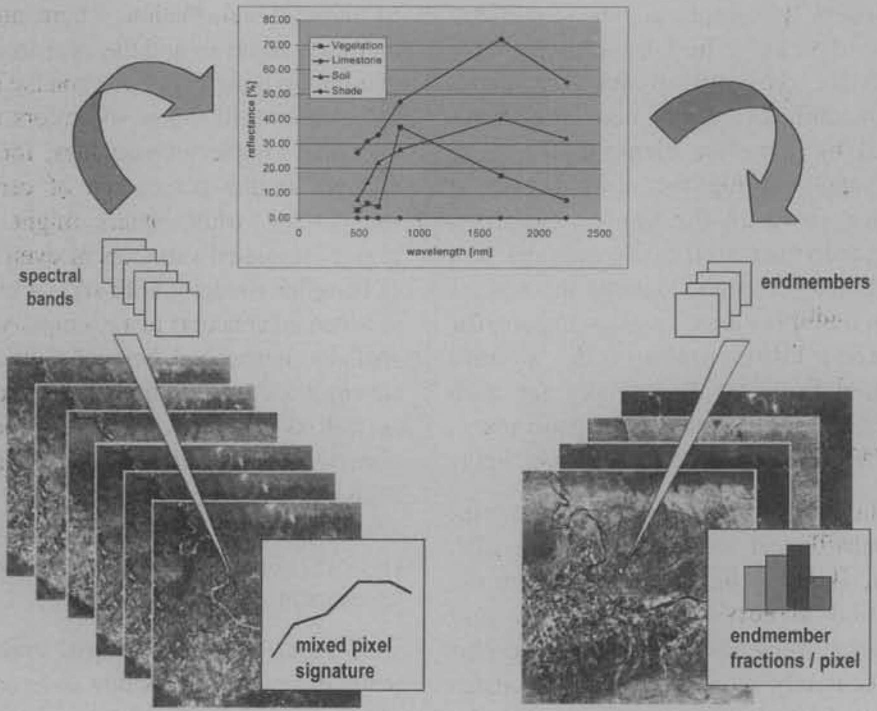

Fig. 10. Converting pre-processed image data into endmember fractions with linear spectral mixture analysis.

it is possible to implement a statistically based analysis approach that determines the fraction of such an endmember in the respective pixel (Adams *et al.*, 1989; Smith *et al.*, 1990).

As a result, we obtain a set of output information layers, each representing the percentage fraction of one endmember on a per-pixel basis (Fig. 10). In some cases, this percentage value might be an indicator in itself, for example when fractions of photosynthetic active vegetation are taken as a surrogate for vegetation degradation over time (see below). Sometimes, they might rather build the basis from which integrated indicators are to be developed or calculated (examples provided under case studies). Regardless of the individual meaning of fraction images, such results are quantitative measures comparable over time and directly related to physical properties of the surface. For example, ground measurements can be employed to ensure a proper spectral characterisation of endmembers in absolutely calibrated imagery.

Case Studies

Only a small subset of potential regional and thematic aspects can be presented in this paper. Generally speaking, we may be able to successfully monitor and assess desertification with remote sensing methods, if indicators can be connected to remotely sensed surface properties or if indicators may be enhanced with remote sensing derived information. The case studies presented below shall give a representative impression about what kind of information can be retrieved with remote sensing based methods and may even be transferred to other regions governed by similar process chains.

The focus is put on two important domains of desertification monitoring and assessment: vegetation and soil. Remote sensing based analyses of vegetation properties are widely applied. Therefore, we would like to put a particular emphasis on deriving consistent information for long-term monitoring of vegetation and on the realisation of ecologically significant parameters (Hostert *et al.*, 2001; Röder *et al.*, 2001). Moreover, we would like to stress that remote sensing based studies not always have to rely on vegetation cover alone as an indicator for desertification processes. For example, Hill *et al.* (1995a) have demonstrated that parameters indicative of soil conditions can be successfully derived from remote sensing data and linked to concepts taken from pedology and geomorphology. The following examples of indicators for desertification processes related with the soil domain can all be associated with such concepts.

Examples are mainly drawn from countries of the European Mediterranean region, also known as "Annex IV countries" of the UNCCD. Additionally, extending the observed climatic range into semi-arid to hyper-arid environments, examples from the north-western Negev Desert and the Dead Sea region in Israel have also been included. While all cases are based on remote sensing driven assessments, studies encompass all spatial scales from ground- to satellite-based assessments and temporal scales from single observations to extended time series.

Ground based hyperspectral assessments: Inorganic carbon content in calcareous soils as an indicator for soil development

Soil loss resulting from a combination of physiographic and human factors is a sign of land degradation. Not only the loss of soil, but also the change in soil physical and chemical properties can be attributed to soil development or soil degradation processes. In the semi-arid and arid Mediterranean most of the area is covered by soils developed from carbonate bedrock. High inorganic carbon content in these environments is one major indicator of soil development standing for degraded or almost undeveloped soil. Thus, the spatial quantification of inorganic carbon has a great importance in the context of desertification monitoring.

Focussing on features detectable by remote sensing techniques, it is essential to bear in mind that the spectral reflectance of soils is affected by the inherent spectral characteristics of various soil components and environmental factors. Among those, soil moisture, organic matter and the varying combinations of mineral components are most significant (Baumgardner *et al.*, 1985). The relations of spectral reflectance and soil properties, like grain size distribution, soil

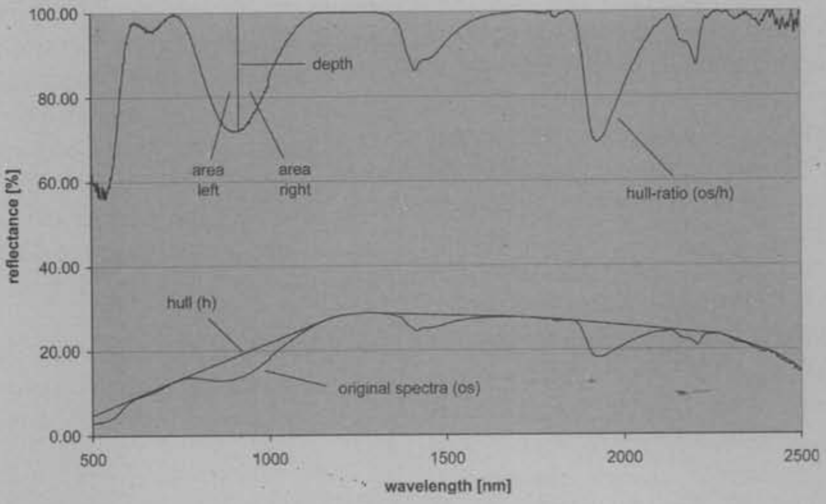

Fig. 11. Example of a convex hull transformation for reflectance spectra and derived absorption parameters

moisture, iron oxides, carbonate content or organic matter, have been outlined in many studies (Al-Abbas *et al.*, 1972; Dalal and Henry, 1986; Ben-Dor and Banin, 1990, 1994; Jarmer and Schütt, 1998).

In the following, a methodology is developed to analyse inorganic carbon content in soils by means of close-range remote sensing techniques on the basis of hyperspectral field or laboratory measurements. Relationships between inorganic carbon content and spectral reflectance from characteristic absorption features of carbonate have been analyzed to detect inorganic carbon using reflectance spectroscopy. An example is given on the basis of semi-arid to hyper-arid climatic conditions at a test site in Israel.

Soil sampling was performed along a transect following a hypsometric rainfall gradient from east of Jerusalem to the Dead Sea. Sampling of surface soil material (2 upper centimetres) was conducted along slope transects on hard calcareous bedrock, taking into account north- and south-facing slopes. Spectral reflectance measurements of homogenized samples were carried out in the laboratory with an ASD FieldSpec II spectroradiometer in the wavelength range from 350 to 2500 nm.

Carbonates show a strong diagnostic absorption feature at 2300-2350 nm. This absorption feature is caused by an overtone of the carbonate ion and its band position is varying according to the composition of different carbonates in the soils (Hunt and Salisbury, 1971; Gaffey, 1986). Calcium-carbonates give rise to a maximum absorption at approximately 2340 nm while increasing contents of magnesium-carbonate shift the wavelength position of the maximum

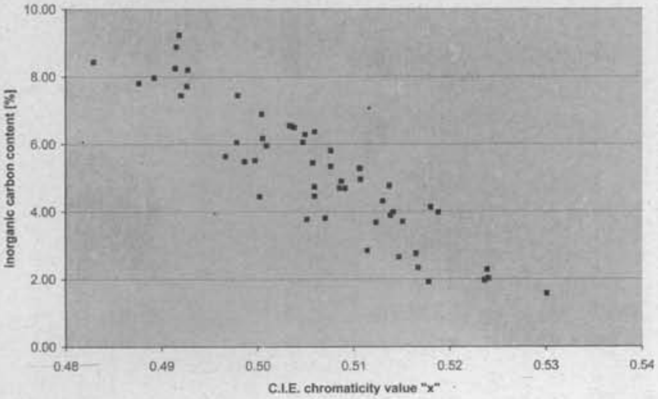

Fig. 12. Relation between C.I.E. chromaticity value "x" and inorganic carbon content

absorption towards shorter wavelengths (van der Meer, 1996; Clark, 1999).

A convex-hull function was applied to standardize reflectance spectra and derive individual absorption features like wavelength position of maximum absorption, maximum absorption depth, feature width, and absorption area of the carbonate absorption band (Fig. 11). Reflectance measurements were converted into trichromatic values, and expressed in terms of the "Commission Internationale de 'Eclairage [C.I.E.]" color notation (x, y, Y). In this color system, "x" and "y" are so-called "chromaticity coordinates", while color intensity is characterized by luminance "Y", which represents color brightness (Wyszecki and Stiles, 1982).

Prediction of inorganic carbon based on the derived parameters from carbonate absorption bands was performed on a regression-based approach. The absorption depth data have been transformed into logarithmic values, since the maximum absorption depth rises exponentially with increasing inorganic carbon concentration. The best result was obtained with a cross-validated r_{cv} of 0.875 when using the maximum absorption depth ($RMSE_{cv}$=0.687; n = 53).

It is well known that inorganic carbon strongly influences soil brightness. But increasing contents of inorganic carbon also affect the chromaticity value "x" (Fig. 12). Therefore, the C.I.E. chromaticity value "x" was included in a multiple regression approach to predict inorganic carbon. The resulting cross validated r_{cv} of 0.955 and $RMSE_{cv}$ of 0.411 exhibited the enhanced prediction accuracy of this model (Fig. 13).

Concluding, it has been proved that spectral features may be successfully

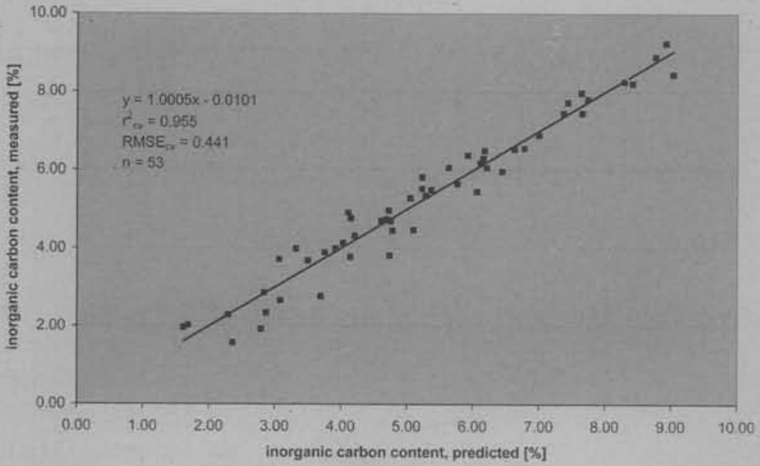

Fig. 13. Cross validation scatterplot of a model for predicting inorganic carbon content

employed to predict inorganic carbon. The integration of C.I.E. chromaticity values even improved the use of absorption features derived from the characteristic carbonate absorption band around 2330 nm. Thus, spectral detection of inorganic carbon content in soils on calcareous bedrock is possible with high accuracy from hyperspectral measurements. However, it has to be taken into consideration that predictions are strongly influenced by the homogeneity of the bedrock material and that more heterogeneous conditions will lead to a decreasing accuracy in the results.

In the future, the variables employed could also be derived from hyperspectral images, to spatially explicitly detect inorganic carbon content over large areas. The calculation of C.I.E. values is even possible on the basis of operational satellite systems such as Landsat Thematic Mapper. Future evaluations have to prove, in how far such an approach may lead to a prediction of inorganic carbon levels in top soils from widely available data sources.

Determining soil fractions and microbiotic soil crusts from aerial photographs as indicators for dune system dynamics

Approximately 20% of the world's arid zones are covered by eolian sand (Pye and Tsoar, 1990). Mobile sand constitutes an extremely poor habitat for plant growth because it contains very small quantities of fine grained particles, organic matter, and nutrients (Danin, 1996). In such an environment, the ecological importance of microbiotic soil crusts like the ones occurring in the Nizzana sand field of the western Negev (Israel) is mainly related to their resistance against erosion caused by wind or surface runoff. Unlike vascular plants, their cover is not reduced in drought years, they do not dissolve when wet, and thus contribute substantially to the protection of unconsolidated and highly erodible substrates in drylands, which are frequently prone to desertification processes (Belnap and Gillette, 1998). The crusts are semi-permeable and, depending on the parent substrate, tend to concentrate runoff and quite efficiently protect infiltrated water against excessive evaporation (Verrecchia *et al.*, 1995).

Garcia-Pichel and Belnap (1996) showed that biomass and activity in biological soil crusts are usually concentrated within 3 mm of the soil surface. This suggests that, if relations between optically active key variables and crust development can be identified, optical remote sensing can not only be used to assess the presence of biological soils crusts, it can also help to differentiate various crust types, thereby providing important information on areas of stability and disturbance in arid ecosystems. Mapping the spatial extent of these areas is highly relevant for sustainable land management and development projects.

The study site is located in the north-western part of the Negev Desert at the border between Israel and Egypt. Average annual rainfall in the region is fluctuating around 100-150 mm; precipitation is highly irregular and mainly occurs between October and May. The west-east oriented longitudinal dunes have an average altitude of 200 m asl and are separated by interdune depressions. The upper part of the dunes is composed of unconsolidated sand, and it is almost devoid of any vegetation, while the dune base and the interdune area are more densely vegetated and to a large extent covered by the biological crust. The interdunal depressions are further characterized by inactive dunes, scattered nebkha, and non-vegetated flat (playa) surfaces with predominantly fine-grained sediments (Yair, 1994; Veste, 1995; Danin, 1996; Yair *et al.*, 1997).

Standard aerial photographs from 1992, 1996, and 1997 were scanned, geometrically and radiometrically corrected, and analyzed through spectral unmixing (Hill *et al.*, 2000). Without further considering the methodological constraints connected with such imagery, it is necessary to note that the (theoretical) maximum number of endmembers in an unmixing approach is restricted to the number of the original spectral bands plus one. For statistical reasons, the maximum number of endmembers used with the aerial photographs was three (Drake and Settle, 1989; Smith *et al.*, 1990; Settle and Drake, 1993).

First, the most important surface components were selected, representing sand, fines (silt and clay), cyanobacteria (concentrated biologic material from the crust), photosynthetic active vegetation, and woody plant components. The respective hyperspectral field and laboratory measurements were resampled to the spectral bandpasses of the aerial photographs. Next, it was compulsory to circumvent the restricted number of spectral endmembers: On one hand, the grain size distribution in soils was considered to be an important indicator and on the other, microbiotic crusts and vegetation components had to be incorporated. Hence, a stratified approach was chosen, as a three-endmember-model did not appear to

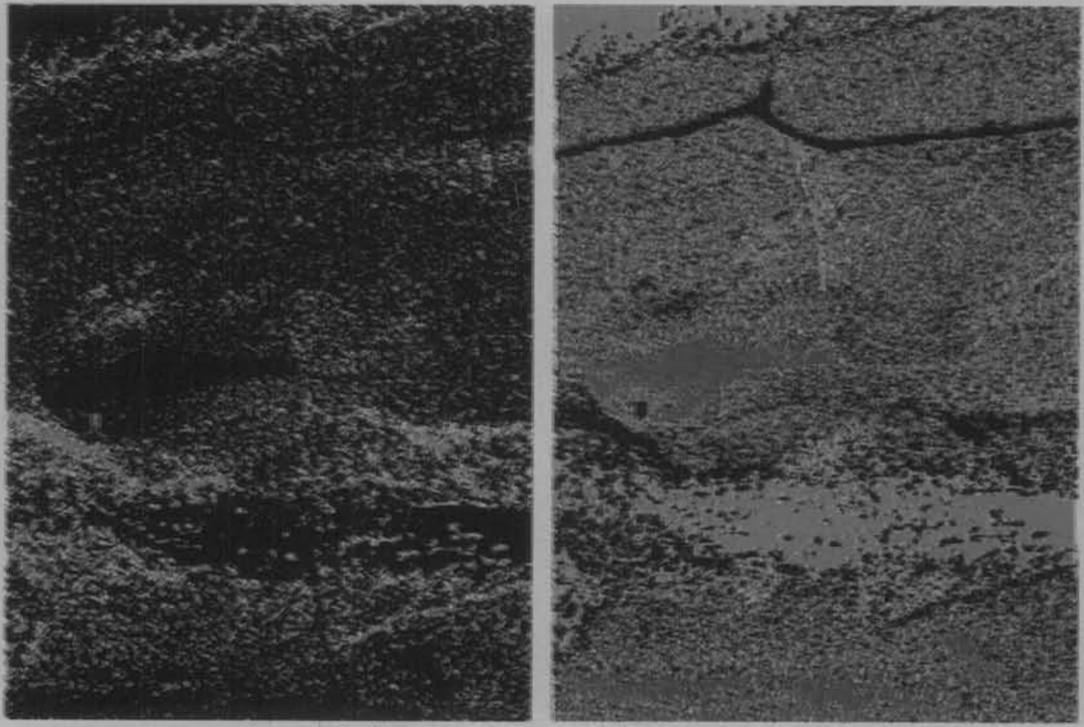

Fig. 14. Vegetation domain (left): sand (red), photosynthetic vegetation (green), woody vegetation (blue); substrate domain (right): sand (red), cyanobacteria (green), silt/clay (blue) (from Hill et al., 2000).

be appropriate for explaining all significant surface constituents.

Based on a simplified foreground-background mixing model (involving only a bright substrate and a dark vegetation spectrum) a mask was produced. The two strata separated vegetated from non-vegetated image areas in a way that more specific endmember combinations could be used for a detailed analysis of the plant and substrate domain (Fig. 14). Two vegetation spectra (photosynthetic and woody) and one substrate component (a 50:50 additive mixture of sand and silt/clay) were used to represent the background signal for the vegetated domain. Three spectral components (sand, fines, and cyanobacteria) were chosen to model the composition of the soil surfaces for the substrate domain.

Beside the active dune (red, due to the dominance of sand) and playa surfaces (blue, dominance of fines) one can distinguish a full range of tonal differences, where the predominance of greenish tones indicates areas with strongly developed biological crusts; yellow and cyan tones represent areas where the biological crust incorporates respectively more sand or fines. Disturbed areas, either caused by car access and trampling or wind erosion in the old dune complexes of the interdune area, become visible through their reddish coloring. Thus, we are able to derive precise maps of crust types which provide clear indications of ecosystem characteristics and specific process domains.

Similarly, we also find that the spectral unmixing of the vegetated domain well documents the spatial distribution of the perennial vegetation in the Nizzana dune field. The most important aspect of the methodological approach is that it provides estimates for both, photosynthetically active and senescent (i.e., woody) vegetation components. This is a clear advantage in comparison to conventional vegetation indices being only sensitive to photosynthetic active vegetation and which have frequently been criticized for being biased to the spectral properties of the plant background (Price, 1993).

Accordingly, different plant components are discriminated in the domain-specific unmixing approach, thereby providing separate estimates of living, dead and total plant cover. Considering the spatial distribution of perennial plants, it becomes obvious that shrubs with considerable photosynthetic activity tend to cluster along the dune base where the infiltrated rainfall from elevated parts of the dune can be tapped by the plants. The interdune depression exhibits a considerable amount of smaller shrubs dominated by dry woody material.

Summarising, the proposed interpretation scheme opened up a unique way to analyze the most important surface components in the Nizzana dune system. Specifically, the interpretation of both domains, vegetation and substrate, contributes to a deeper understanding of dune system dynamics, stability and change.

Hyperspectral airborne remote sensing: Organic carbon content of soils as an indicator for degraded semiarid ecosystems

Hyperspectral remote sensing systems like DAIS-7915, HyMap, or AVIRIS considerably extend the possibility for mapping soil properties. Nevertheless, some fundamental uncertainties arise when statistical methods are used to analyze hyperspectral data quantitatively (Martens, 1989). Usually no single wavelength is sufficient for an accurate prediction of heterogeneous components like organic carbon. Consequently, multivariate models are preferred. These techniques need to deal with collinearity among the reflectance values, and thus require a statistical wavelength selection. An interactive selection of the respective bands often fails since our understanding of information content of such data may be incomplete or even wrong. The most widely used techniques for quantitative purposes are Stepwise Multiple Regression (SMR), Principle Component Regression (PCR), Partial Least Squares Regression (PLSR), and Artificial Neural Networks (ANN).

In this case study, an ANN model was trained employing laboratory reflectance spectra and a set of chemical reference data. The model was then transferred to image data of the DAIS-7915 sensor to map the organic carbon content of top soils in the Guadalentin drainage basin, which is located in the Betic Cordillera of Spain. The watershed is known to belong to the most arid parts of the European Mediterranean. Annual rainfall in the lowlands of the Guadalentin totals in average 300 mm. As typical for areas with small rainfall amounts, soil forming processes occur at very low

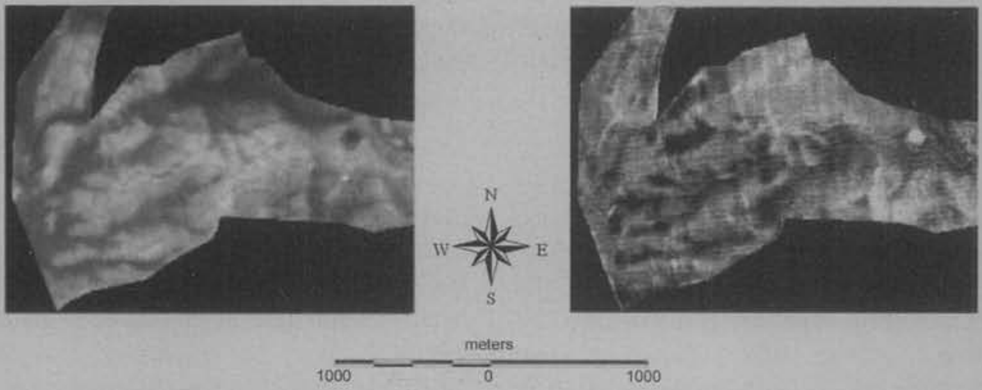

Fig. 15. Test area with bare soils from a DAIS-7915 image (left, reflectance in the visible domain) and predicted organic carbon content (right); grey levels vary from black (0% carbon content) to white (1.5% carbon content)

rates. Soils are dominated by calcaric lithosols and regosols on sloping terrain; calcaric fluvisols are abundant in depressions or along the main river courses. Slopes are covered by *Stipa tenacissima* and predominantly grazed. Most recently, accelerated soil erosion affects large parts of the region and has caused extremely high rates of siltation. The neighbouring reservoirs Pantano de Valdeinfierno and Embalse de Puentes, both built in the early 19th century, are as a consequence filled up with sediments today.

A field campaign was launched parallel to a DAIS-7915 flight in June 1997 to supply reference measurements for data calibration and the application of rigorous atmospheric corrections. In the study area about 100 soil samples were taken for organic carbon analysis and for reflectance measurements with a high spectral resolution ASD FieldSpec II spectroradiometer in the laboratory. The spectral data were resampled corresponding to the position, number and characteristics of the DAIS-7915 spectrometer bands. The signal-to-noise ratio was adjusted to the equivalent noise level in the real image data by investigating the variability in several homogeneous image areas.

A min-max normalisation was carried out, since organic carbon predictions turned out to be more precise with normalized spectra. It is well known that high contents of organic matter and free iron oxide reduce reflectance intensity in the wavelength range between 500 and 1200 nm, causing a strong influence to the shape of the spectra in the visible (VIS) and near infrared (NIR) (Al-Abbas and Baumgardner, 1972; Baumgardner *et al*., 1985). ANNs seem to be able to link shape information of the normalized reflectance curve to the sample's organic carbon content. The training of a three layer feedforward ANN (40-4-1) was accomplished using the resilient backpropagation learning-algorithm (Riedmiller and Braun, 1993). A cross-validation was accomplished by a "leave 10 out" rotating scheme.

Using the full spectral resolution of 72 bands in the reflective wavelength domain of the DAIS-7915 sensor and with disrespect to the real signal-to-noise ratio, the relationship between measured and predicted organic carbon contents was close (R=0.85). Cutting the spectra at 1703 nm and considering the signal-to-noise ratio of the sensor, the model quality declined (R=0.75). The transfer of this model to real image data of the DAIS-7915 sensor resulted in a map showing distinct patterns of the predicted organic carbon values. For the time being, this transfer has been implemented for areas covered by bare soils only (Fig. 15).

Though absolute values should be regarded with caution, the results show distinct patterns of varying soil organic carbon contents with strong correlation to terrain features. These patterns reflect typical sequences of eroded ridges, depressions, and plateaus covered with xeromorphic soils. The resulting map shows higher contents of organic carbon corresponding to terrain facets with converging water flow, which mark sink areas with deposition as the predominating process (concave slope elements). Conversely, areas with diverging flow directions (active erosion zones) exhibit constantly lower organic matter contents (Pickup and Chewings, 1988).

Such findings are consistent with other assessments and can be regarded as an important step in upscaling quantitative monitoring approaches from ground based over aerial surveys to methodologies based on satellite remote sensing. In this context, advanced models have recently been developed to estimate soil organic carbon from satellite based data and to link spectral surface characteristics with soil erosion processes (Hill and Schütt, 2000).

The results demonstrate the potential of hyperspectral data analysis for retrieving soil organic carbon in semiarid environments. The selected methodology cannot replace traditional analytics. However, it may be successfully employed as a screening method to receive a quick overview, solely based on mono-temporal remote sensing data, providing a set of reference analytic data is available for the calibration of a statistical model.

Satellite based analysis of vegetation cover changes as an indicator for grazing induced land degradation

The Mediterranean Basin in general and Greece in particular are among Europe's oldest settlement areas. Especially in Crete, there is a long history of human influence on the mountainous ecosystems which have been extensively studied by many research groups (e.g., Papanastasis *et al*., 1990; Strid *et al*., 1995; Bergmeier 1998; Egli 1998; Tsiourlis *et al*. 1998). More recently, subsidies by the European Communities contributed to a rise in sheep and goat grazing. Furthermore, road building has improved accessibility of remote areas and livestock is transported into areas that were less intensely managed before. Although it is known that grazing increased, it is not well understood how grazing pressure differs spatially, and in how far corresponding processes altered the landscape of Crete during the last two decades. Hence, one major focus of research is to study the influence of grazing on the development of Crete's rangelands.

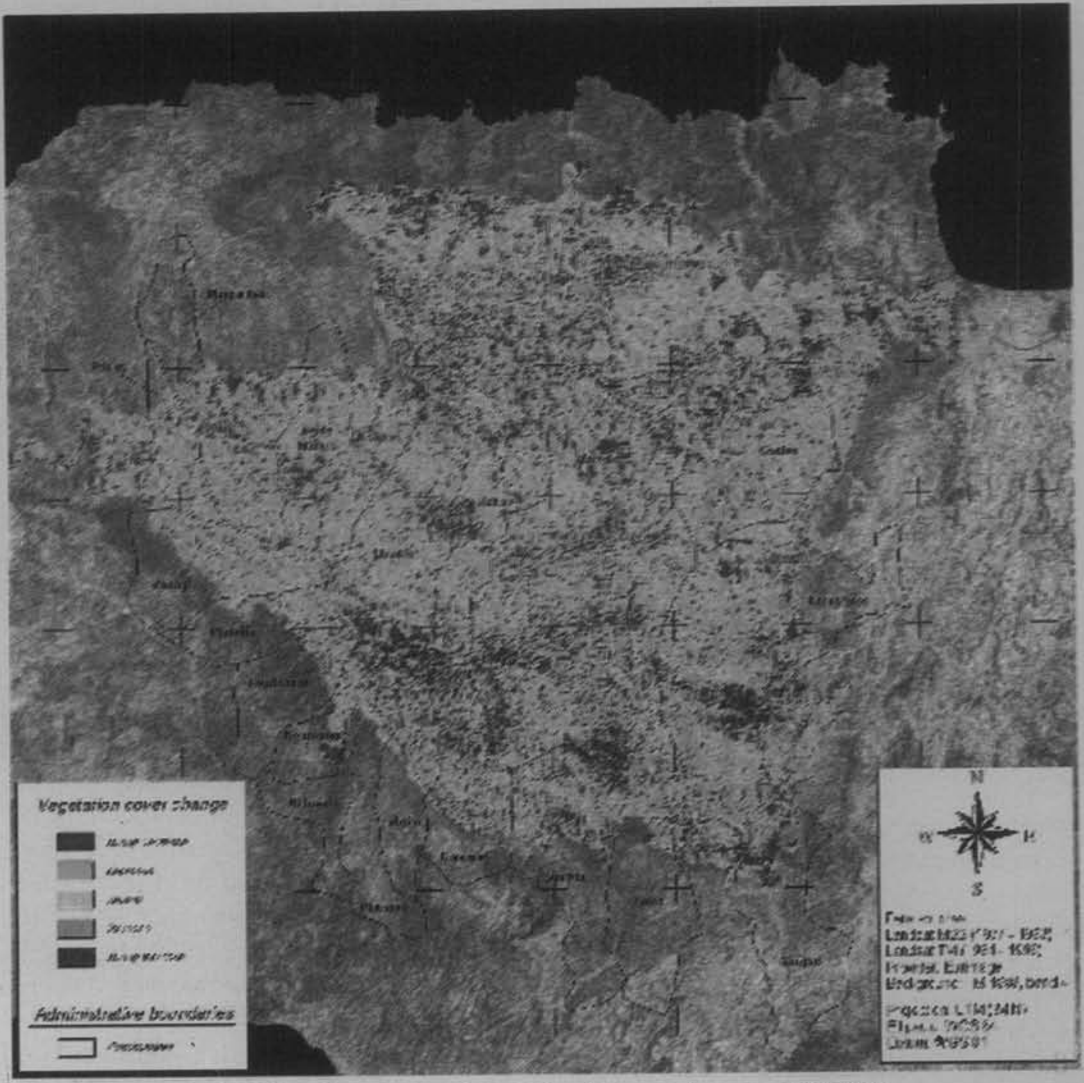

Fig. 16. Map of vegetation degradation for central Crete, 1977-1996.

While many case studies at plot scale level have shown the strong link between landscape development and human influence, it is often not straightforward to monitor degradation processes taking effect on smaller spatial or longer temporal scales. One way to overcome such restrictions is an analysis strategy based upon retrospective satellite remote sensing and GIS, as for example proposed by Hill (1996) and Hill *et al.* (1998).

One of the major rangelands of central Crete has been selected to serve as a test site for answering these questions: the Psiloritis Mountains, the main mountain range in the heart of Crete. The Psiloritis range is an extensively grazed area and its history of human influence dates back to Minoan times. Livestock husbandry can be regarded as the main economic activity and almost all areas not suitable for agriculture are under grazing regimes (Lyrintzis and Papanastasis, 1995).

The analysis was based on a set of nine Landsat-5 TM (1984-1996) and five Landsat MSS scenes (1977-1988), all recorded in late spring. Auxiliary data comprized a SPOT-derived digital elevation model (DEM) of central Crete and a corresponding orthophoto. The DEM was employed to derive maps of aspect and slope. The geology of the same area was digitized from 1:50,000 scale maps. Field based data on vegetation cover and species distribution were provided for several plots and transects. Numerous hyperspectral measurements of soils, rocks and vegetation (photosynthetic active and non-photosynthetic) were collected during three field campaigns, georeferenced with GPS and stored in a GIS.

Data analysis followed the above specified scheme and yielded fraction images of photosynthetic active vegetation, soil, and limestone. The vegetation fraction images have been combined in a time series analysis to yield a linear regression on a per-pixel basis. Thus, it was possible to derive not only mean values of vegetation abundances, but also spatially explicit trend functions indicating the development of grazed vegetation during the monitored 20-year period. Vegetation development was categorized into changes taking place gradually and those occurring on a much shorter time-scale. The latter have mainly been caused by singular events like wildfires, intentional burning or mechanical clearings to create horticultures or olive plantations. Developments over several years or even over two decades may rather be related to processes like grazing and the associated socio-economic triggers such as changes in infrastructure, subsidies, etc. (Hostert *et al.*, 2001).

Long-term trends have been investigated more closely by combining the trend direction with its magnitude and average level. To support a synoptic interpretation of these information layers, a degradation index was defined, representing different degrees of degradation starting from a significant decrease on a low level of vegetation cover to a significant increase (Fig. 16). Extreme levels of degradation were found along the northern plateau of the Psiloritis massif in elevations between 800 and 1500 m asl.

A GIS-based analysis of boundary conditions reveals that vegetation degradation does not occur in areas where stress levels tend to be higher such as on south-facing slopes or in elevated areas with short vegetation periods. Decreasing vegetation cover is rather typical for sites with good water supply, developed soils and a moderate local climate. Apparently, favorable natural boundary conditions coincide with degrading vegetation levels. On the other hand, these areas correspond very well with the main grazing zones which are centered around a few communities in this part of the Psiloritis Mountain. A comparison of livestock husbandry statistics on community level reveals that over 60% of the animals in the Psiloritis Mountains are concentrated in 4 communities. These villages at the same time represent the core area of vegetation degradation processes.

It can be concluded that the significant increase in the number of grazing animals along with a highly improved accessibility of formerly remote mountainous areas has

Table 2. Empirical relations between green vegetation cover and different biomass and necromass parameters ($t\ ha^{-1}$)

	Total biomass	Leaf biomass	Woody biomass	Necromass
All stations	$y = 0.1344\ x$ $R^2 = 0.79$	$y = 0.0194\ x$ $R^2 = 0.83$	$y = 0.1156\ x$ $R^2 = 0.69$	$y = 0.0265\ x$ $R^2 = 0.61$
Phrygana I*	$y = 0.1014\ x$ $R^2 = 0.99$	$y = 0.0225\ x$ $R^2 = 1$	$y = 0.0784\ x$ $R^2 = 0.99$	$y = 0.0194\ x$ $R^2 = 0.70$
Phrygana II	$y = 0.1397\ x$ $R^2 = 0.69$	$y = 0.0181\ x$ $R^2 = 0.50$	$y = 0.1231\ x$ $R^2 = 0.59$	$y = 0.0106\,x + 0.5786$ $R^2 = 0.16$
Phrygana III*	$y = 0.1551\ x$ $R^2 = 0.95$	$y = 0.0182\ x$ $R^2 = 0.91$	$y = 0.1374\ x$ $R^2 = 0.90$	$y = 0.0342\,x + 0.0007$ $R^2 = 0.97$

I: low diversity phrygana with *Sarcopoterium spinosum*
II: medium diversity phrygana with *Sarcopoterium spinosum*, *Thymus capitatus* and *Calicotome villosa*
III: high diversity phrygana with 5 or more species
*: correlation coefficients above 0.9 are partly the result of low sample numbers

resulted in an increased grazing pressure, which is locally reflected by vegetation degradation. By incorporating available livestock statistics, information on degradation can be related to administrative units, which is mandatory for the definition of concrete management scenarios to support a sustainable utilization of natural grazing resources. Moreover, the pattern of decline, increase and stability of vegetation originating from the trend analysis clearly underlines that degradation monitoring needs to be based on a spatially differentiated approach.

Upscaling Biomass Estimates: An Indicator for Vegetation Degradation Processes

Several studies have demonstrated the potential of remote sensing techniques to derive meaningful soil and vegetation related parameters (Schowengerdt, 1997; Graetz and Gentle, 1982; Pech *et al.*, 1986), and to employ empirical or semi-empirical approaches to yield classical indicator variables, such as LAI, biomass or proportional vegetation cover (Lacaze *et al.*, 1996, Hill, 2000; Hostert *et al.*, 2001). The methodology presented in previous section is one example for characterizing the ecological state of natural areas by means of green vegetation cover as a secondary indicator. While such an approach is well suited to scientific frameworks, green vegetation cover may be too abstract when political and management authorities are addressed. In order to supply administrative bodies with adequate information on ecological resources and processes, the goal must be to do so on the basis of an easily comprehensible and clearly defined parameter or indicator, such as biomass, which is used in this context.

Biomass may be defined as the total measure of all living plants and animals in a given unit. While, strictly, there is a further distinction between phytomass, referring to plants exclusively, and biomass also including zoomass, this is often neglected since usually plants make up for 99% of the total biomass (Schulz, 2000).

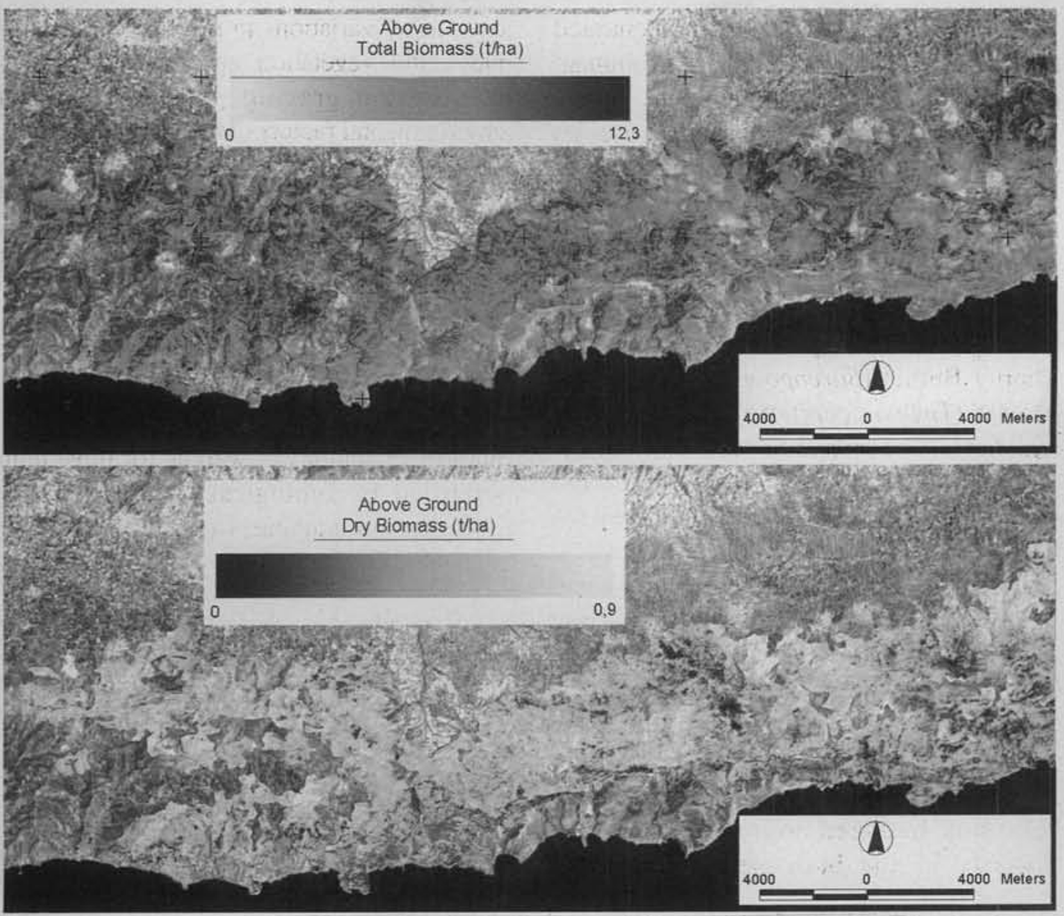

Fig. 17. Maps of biomass (top) and necromass (bottom) for the Asterousia Mountains of southern Crete (from Röder et al., 2001).

Here, biomass only refers to plant biomass, which has been further distinguished into total, green, dry and dead biomass, the latter correctly being termed "necromass". While information on biomass parameters is essentially based on field-based assessments or published data, the objective was to establish a parameter common to both field assessments and remote sensing techniques as a link to support upscaling of point-related field data to a larger spatial context. In the approach presented here, the proportional amount of green vegetation cover is employed.

In the framework of the European research project DeMon-II, the Asterousia mountain range of central Crete was chosen as the target area. The case study was based on a Landsat-TM dataset, which had been geometrically and radiometrically rectified. Following SMA was employed to derive estimates of green vegetation abundance to quantify green vegetation cover of woody green vegetation.

The field estimations were concentrated on 18 stations representing the predominant phryganic vegetation communities in the Asterousia mountains with different species diversity. For all stations, different above-ground biomass parameters were measured, as well as the ground cover for the respective station. In order to adequately consider the most common woody phryganic species, five representative species were employed: Thorny Burnet (*Sarcopoterium spinosum*), Thyme (*Thymus capitatus*), Spiny Spurge (*Euphorbia acanthothamnos*), Little Sage (*Phlomis lanata*) and Jerusalem Sage (*Phlomis fruticosa*). Of these species, a large number of individuals were measured according to their length, width, height and area covered. Then they were cut from the root, weighted in the field, oven-dried and separated into the biomass (leaves, woody parts, seeds) and necromass (dead tissues) parts, which were again individually weighted. For each species allometric relations between biomass and mean diameter of the bush were calculated.

In a second step, for each of the 18 stations, 10 transects were laid with a length of 50 m each. Along these transects, the species, their sizes and cover as well as their spatial extension were sampled, and the individuals grouped according to their mean diameters. The derived group-wise relations were then employed to calculate the biomass parameters for each of them. Multiplying these by the share of each group of the total area yielded the average of biomass and necromass in t/ha for each of the stations, along with the average projected ground cover of woody green vegetation. Calculating the values based on groups of similar species sizes minimizes the influence exerted by variations in the size of different phryganic vegetation species, which may result from grazing pressure or other environmental factors (Tsiourlis *et al.*, 1998).

The resulting dataset, comprising extensive information on cover, size and biomass parameters was included in a regression analysis to compute linear relationships between cover and biomass. The mapping of dominant species and species distribution for all stations allowed to compute regression functions for the total number of stations as well as for three units stratified by biological diversity of the phrygana communities found at the different sites (Table 2).

It is obvious that the cover-biomass relations derived for units stratified by species diversity partly exhibit a stronger correlation. However, Landsat TM data do not permit a species-level assessment of vegetation and the functions derived for all 18 stations are statistically more sound. Consequently, functions including all stations have been employed in the further processing.

These empirical relations have then been applied to the estimates of proportional green vegetation cover derived from Spectral Mixture Analysis of a radiometrically corrected Landsat TM image. Hence, it was possible to produce spatial maps of total-, leave-, and woody- above ground biomass and necromass in t ha^{-1} at a grid size of $30*30\ m^2$. Additionally, maps of dominant vegetation communities derived from aerial photography can be used as an auxiliary data source to enable the masking of areas dominated by non-phryganic vegetation communities, for example in narrow valleys with different water regimes, for which the derived relations are not valid. The resulting maps delineate the amount and distribution of above ground total, leave, woody biomass and necromass, respectively (Fig. 17).

In order to attain a quantitative validation of the result, a reference map of vegetation cover was produced based on synoptic visual interpretation of a multispectral Landsat-TM image and a SPOT-Orthophoto. The resulting polygons representing homogeneous vegetation units were assigned six vegetation density classes, based on 250 samples of vegetation density mapped in field according to the same classes and located with GPS. The vegetation map resulting from SMA was classified into the same categories, and the resulting values for all pixels were compared with the value found in the corresponding polygon in the reference map by applying zonal statistics. The results confirm the validity of the unmixing-based vegetation estimates, with 74% of all values corresponding to the field-based class assignments, and another 23% being misjudged by one class only.

This example demonstrates the potentialities resulting from the combination of dedicated quantitative remote sensing techniques with traditional field ecology to perform a spatially explicit assessment of biological resources. However, it has to be acknowledged that the validity of the results depends on the statistical significance of the input data, so that a major focus has to be set upon the accurate pre-processing of the satellite data, and most of all on the analysis of a large enough number of field samples. Since the latter is very resource-intensive in terms of manpower, it can be considered the major bottleneck of the approach. It may very often not be possible to conduct both extensive field studies for the collection of input data and additional, independent field measurements to assess the validity of the maps produced. Notwithstanding these constraints, the establishment of green vegetation cover as a link between remote sensing derived secondary indicators and field-based biomass measurements is a major step in the upscaling of detailed, plot-related information to a much larger scale.

The Human Dimension - Relating Pressure and State Indicators

It has been shown that a sound framework is necessary to chose the right indicators, to interpret data in a reasonable way, and to assess regional desertification processes adequately. Examples have been deliberately drawn from different environments and at various spatial and temporal scales to demonstrate the wide scope of remote sensing driven assessments. However, as already indicated in the beginning of this paper, monitoring and assessment in itself is only one important component in combating desertification.

Anthropogenic influences must be regarded as an inherent factor in desertification studies. This directly leads to the necessity to integrate knowledge and data about socio-economic boundary conditions with information about the state and development of the natural environment. While the latter has to be derived from field based work, remote sensing data, GIS-based analysis, or modelling approaches, the human dimension is often difficult to assess quantitatively. Nevertheless, if we do not want to settle with understanding the effects of processes on the environment, but also want to elaborate why these processes are occuring and how land degradation or desertification may be turned into sustainable development, there is no alternative to linking state indicators with pressure indicators.

Qualitative and quantitative measures of socio-economic background information should be used to pinpoint triggering processes of desertification. In some cases remote sensing based information may be directly related to socio-economic indicators. Satellite based monitoring of clear-cuts for growing cash crops or developing fruit plantations may be one example, intentional burning to open forested areas for grazing a second one.

As desertification is a long-term phenomenon and data supplies in many regions of the world are limited, indigenous knowledge may often be an important source to consider (UN, 2001). Carefully elaborated sampling schemes will assist in collecting "objective" information from local sources that will also help to properly interpret additional datasets, such as socio-economic base data. In many regions of the world, periodical statistics and censuses are the basis of such resources. Socio-economic indicators at different administrative levels, e.g., based on entire countries, on provinces or districts, or even on communities should hence be linked to findings from other information sources whenever possible.

Future Developments

Remote sensing and GIS stand for a dynamic technological, methodological, and scientific development and have been subject to rapid change and progress since their advent. It is hence difficult to predict in particular how changes in future system design or advances in related methods may expand our options in desertification monitoring and assessment. Nevertheless, it is possible to draw a general future scenario on geoinformation science and its potential impact on different disciplines.

It is probably most useful to look at future developments from various angles. Considering the ongoing improvements in sensor technology, forthcoming sensor generations will enhance our perspective in means of spatial and spectral resolution, in spatial and temporal coverage and in data accuracy (Fritz, 1996; Aplin *et al.*, 1997; Cary, 1997). The introduction of operational spaceborne hyperspectral systems will allow for accurate surface component analysis based on absorption features as well as better general spectral differentiation. Moreover, spectral sensor enhancements will drive new developments relying on remote sensing based modelling approaches. The same applies to enhanced data accuracy, as many models featuring remote sensing based information oblige sensitive key input parameters.

Not only space- or airborne systems and the respective data will change; also software systems, their design, and their capabilities are important issues to be considered. While on one hand today's image processing and GIS software packages include an enormous wealth of functions, they on the other hand often lack the needed functionality. This fact is for example reflected in many users operating two or more systems to fulfil their demands. Today, major advances are still to be made in the context of system integration. Even though many vendors describe their systems as "hybrid", only few really feature sufficient capabilities for handling and processing both raster and vector data in a decent way. However, initiatives like the Open GIS Consortium (OGIS) have already initiated standards helping to overcome the widespread separation of methods or systems and will hopefully achieve even more in the future.

With many systems being based on personal computers and standard operating systems today, costs become even more focussed on data acquisition. In the past, data costs have impeded many developments based on remote sensing technology, above all in countries most affected by desertification in Africa, Asia, or South America. It has only been recently that several data providers indicate their will to alter data distribution and pricing policies in the future. Some vendors have already changed product prices or have started to distribute data for free among the scientific user communities. Important examples are the reduced costs for Landsat data or the recently opened archives of SPOT Vegetation, offering terabytes of global coverage data for free.

Finally, of course, internet based developments will force an enhanced propagation of products and data. In many cases, data distribution pathways have already shifted towards internet based solutions, as for example in the case of Terraserver, with world-wide data being sold through an internet based gateway. Though, the options of stimulation through the world wide web are not restricted to data distribution and exchange. Also remote sensing and GIS based technology itself will profit from new opportunities, such as distributed data processing, internet based analysis or enhanced information dissemination. We can imagine that today's software extensions attaching internet functionality to expert systems will turn into internet extensions connecting digital image processing or GIS capabilities to www standards.

Concluding, we may say that there is an exciting future ahead. New options for desertification monitoring, assessment, and related topics will gain recognition and some will positively stimulate these fields of research. Remote sensing and GIS based research will not provide an all-in-one solution of long asked questions, but will hopefully contribute in manifold ways to integrated and consistent research results.

Acknowledgments

Examples in this text are based on several research projects conducted at the Remote Sensing Department hosted at Trier University, Germany. Namely results from the following projects have been presented:

- *DeMon-II: An Integrated Approach to Assess and Monitor Desertification Processes in the Mediterranean Basin*; funded by the European Commission, DG XII, Environment and Climate (contract ENV4-CT95-0166)

- *ERMES-II: – An Integrated Methodology for Projecting the Impact of Climate Change and Human Activity on Soil Erosion and Ecosystem Degradation in the Mediterranean: A Climatological Gradient and Dynamic Systems Approach*; funded by the European Commission, DG XII, Environment and Climate (contract ENV4-CT95-0181)

- *Monitoring recovery processes and rates of a disturbed sandy arid ecosystem*; funded by the German-Israeli Foundation for Scientific Research and Development (G.I.F.)

Without external funding the results presented in case studies would not have been achieved and this support is greatly acknowledged.

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