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Remote Sensing and Geomatics Concepts for Desertification and Land Degradation Monitoring and Assessment

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Introduction

Desertification, as a specific expression of land degradation processes, is a concept applied by scientists and policy makers after droughts threatened the Sahel in the last quarter of the 20th century, defined by the United Nations Convention to Combat Desertification (UNCCD) as “the degradation of the land in arid, semi-arid and dry-sub-humid areas, as a result of several factors, including climatic change and human activities”. The dominant symptomatic character of this definition does not account for the underlying processes of the phenomenon. The consequence is that the popular meaning of desertification is often associated with a catalogue of environmental calamities rather than specific distress in the human population-renewable resources system. In such conditions both prospects and mitigation become extremely uncertain.

Purely climate climatic factors were rarely responsible for desertification processes in the Mediterranean region. This is primarily because dry spells are and have been relatively short-lived, and natural ecosystems and agricultural systems have the potential to recover easily. Present land degradation in Northern Mediterranean countries is primarily due to dramatic land use changes that occurred during the second half of this century and which in many cases lead to an unstable state of ecosystems (Brandt & Thornes, 1996). It is widely agreed that socio-economic disturbances, particularly when they occur combined with climatic fluctuations, become the main drivers of desertification (i.e., Reynolds & Stafford-Smith, 2002). They affect water balances and land degradation through changes in land-use patterns. In particular, large areas of Mediterranean rangelands are affected from transitional processes that cause conflicts between past and present land uses or economic and ecological priorities, i.e. between optimised productivity and ecosystem conservation.

Substantial research efforts have been launched and carried out to investigate various aspects of the desertification problem, but it is quite recent that projects have adopted a more holistic concept. Among these we find the LADAMER project that has been launched under the umbrella of the GMES initiative, as well as the Integrated Project DeSurvey to be started in 2005 (both supported by the European Union, DG Research). Both projects are to a considerable extent focussed on remote sensing and geomatics applications in the desertification context (e.g., Hill & Peter, 1996; Hill, 2000), an approach which quite recently has also been adopted by the European Space Agency (ESA) in launching their DesertWatch project.

The Conceptual Framework

A major difficulty of assessing land degradation is inherently related to the very concept, as ‘the loss of the land’s capacity to produce goods and services’. This is a rather unspecific symptom which may involve a large array of processes, each with its own boundary conditions for its detection or monitoring. Land degradation assessment methods have evolved from classic field survey methods for soil and vegetation mapping and land suitability evaluations to the more recent ecological approaches (e.g., Ludwig & Tongway, 1992; Mouat et al., 1992). These ground-based methods score low for most of the practical requirements, but when based on broad field experience, they may yield very accurate results in relatively small areas.

Initially, although it was already recognized in principle that land degradation involved complex interactions between physical and socio-economic process domains (e.g., Perez-Trejo, 1994), a large part of research activities focussed on soil erosion assessments as a core indicator for degradation processes. The European Commission, for example, launched a first attempt to produce exhaustive maps on natural resources and soil erosion risks in Mediterranean Europe (CORINE, 1992). These initial mapping experiments on one hand suffered from methodological shortcomings but also revealed major deficits due to the limited availability of base data layers on European scale. The data availability has meanwhile largely improved (i.e. European Soil Map at 1:1 million scale, CORINE Land Cover, etc.) such that recent research activities like the “Pan-European Soil Erosion Risk Assessment”-Project (PESERA) can build on more solid grounds and are achieving substantially improved results (e.g., Grimm et al., 2001).

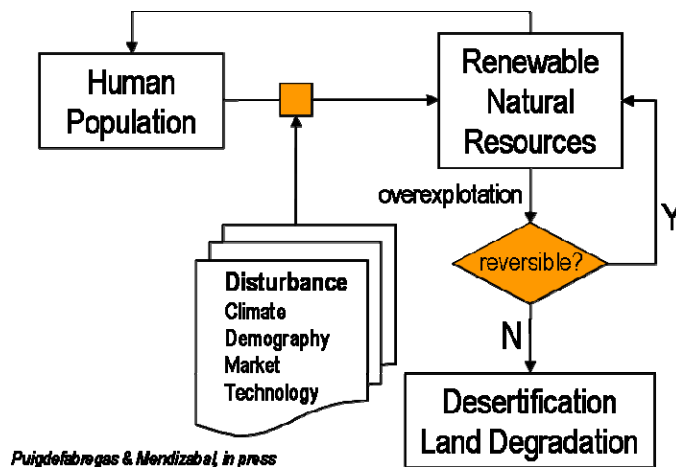


Figure 1. A conceptual view on desertification (from Puigdefabregas & Mendizabal, in press)

Besides, the insight that land degradation assessments must go far beyond the soil erosion issue has grown considerably. Human population and natural renewable resources may be considered two linked elements in a single system, which is affected by climatic or socio-economic disturbances. The former include droughts, rain spells, etc. The latter involve demographic, political, market and technological changes that enable or disenable access to those resources. Under steady-state conditions, intensity and duration of disturbances remain within the range of those that have appeared throughout the history of the system. They have been incorporated in its own evolution, in such a way that it recovers quickly after they have ceased. However, a new or very extreme disturbance or combination of disturbances may happen that takes the system beyond its threshold of sustainability (Puigdefabregas & Mendizabal, in press). This may occur as an increased availability of resources (i.e. a humid period, the introduction of a new technology) an increased demand for products (i.e., higher prices, local increase in agricultural population) or the contrary, as a reduction of available resources (i.e., extreme drought).

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In both cases, resources become over-exploited. If the system is endowed with feedback mechanisms to reverse this condition, it can recover and return to the steady state. Otherwise it falls into an over-exploitation loop that leads to its own extinction. This process, when it happens in drylands, may be considered the core of desertification. Such disturbances or desertification drivers may continue working to date or not. In the first case we are dealing with 'current' desertification. In the second, the forces that drove desertification in the past are no longer at work today. If resilience thresholds of natural resources have not been exceeded, natural recovery is possible, if they have (i.e., extreme soil erosion), we are dealing with 'relict' desertification. In the latter case, the imprints of past desertification are observable today, even after disappearance of the underlying factors. Distinguishing between current and relict desertification is crucial for designing treatment programs. The former require either relieving driving forces or providing the affected systems with capacity for adaptation. The latter need only ecological and economically sound restoration.

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The LADAMER and DeSurvey Approaches

During the past 10 years, the European Commission has funded numerous dedicated research projects in the field of land degradation and desertification which focussed on data collection in specific field sites, detailed methodological studies, assessment and monitoring experiments, and the development of specific modelling concepts. Although substantial scientific progress has been achieved and some projects succeeded to link a considerable number of field sites and case studies across the Mediterranean basin, the scientific community has, apart from few initiatives not been able to provide unifying concepts for assessing land degradation processes on Mediterranean scale as required by political decision makers. Two new projects, LADAMER and DeSurvey, have been launched to address these ultimate objectives.

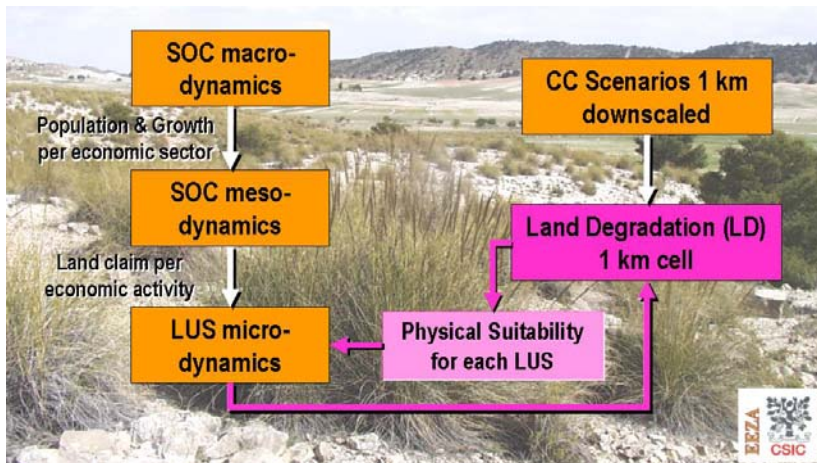


Figure 2. Design of a Dynamic Systems Approach for Land Degradation Assessment followed under LADAMER and DeSurvey

LADAMER (EVK2-2002-0599, see also www.ladamer.org) builds on an integrated approach which combines specific fields of expertise in landscape ecology and soil science, remote sensing, spatial analysis and knowledge system management. The major concern of the project is to identify hot spot areas subject to a high desertification/degradation risk, and to provide an assessment of the present degradation status of Mediterranean lands on small scales. With regard to the substantial progress in data availability and methodological concepts achieved during the past decade it is a major objective of this proposal to provide such an exhaustive assessment. Following this rationale, it is believed that the LADAMER approach might supply products relevant to institutional end-users on national and

international level, by integrating different models and techniques that have already proven their validity on local to regional scale. The major challenge for this integration is that the resulting methodological packages, in order to ensuring their applicability, are required to be objective, reproducible and transferable; include error estimates of the category assignation; be applicable at the regional scale over large areas; and have low data requirements, be cost-effective and easy to apply. Although complemented by additional important topics such as the analysis of climate change impacts, ground-based land condition assessments (model-based approaches), agricultural risk assessments, socio-economic issues, the Integrated Project DeSurvey (see also www.desurvey.net) is a new project platform to further develop and expand the remote sensing and geomatics approaches initiated within LADAMER.

This work basically involves three major components - remote sensing based time series analyses, land degradation modelling and land use / land cover change modelling - that will allow for adequate monitoring, assessment and modelling of land degradation at a European Mediterranean scale.

The Land Degradation Assessment Component

A major difficulty of assessing land degradation is inherently related to the very concept, as 'the loss of the land's capacity to produce goods and services'. This is a rather unspecific symptom which may involve a large array of processes, each with its own boundary conditions for detection or monitoring. Land degradation assessment methods have evolved from classic field survey methods for soil and vegetation mapping and land suitability evaluation to the more recent ecological approaches. These ground-based methods score low for most of the practical requirements, but when based on broad field experience, they may yield very accurate results in relatively small areas.

Current knowledge of land degradation processes, particularly concerning runoff and soil erosion, has already been incorporated in a range of distributed physically-based models, such as ANSWERS, SHE, KINEROS, LISEM and MEDRUSH. These models can provide theoretical insight in complex cause and effect relationships and may be suitable to catchment scale case-studies on land degradation. Besides the fact that they are only addressing a facet of the land degradation problem they are also too demanding, in terms of input data, model implementation and calibration, to be an option for national and trans-national assessment studies. The characterisation of terrain form and topographic position has been an almost intrinsic part of land surveys for a long time. More recently, the use of digital elevation data and derived terrain attributes for the modelling and prediction of runoff and sediment transport patterns has been advocated. These approaches score better on many of the practical requirements and are especially suitable for the identification of potential hazard zones, but cannot be used for the monitoring of change.

The vegetation cover interferes more or less directly with all water loss processes at a site in order to optimise to a certain extent the local water availability for their own benefit, an optimisation process which involves several sub-processes and feedback mechanisms. Recently, in the frame of the MEDALUS project, a theoretical framework for land degradation assessments has been developed (Boer, 1999) which relies on these vegetation functions to estimate the local water balance, in terms of rainfall to evapotranspiration ratios. Experience with the application and qualitative evaluation of this method was obtained in a medium sized area (1000 km²). The approach is innovative in the sense that it provides a process-oriented, rather than descriptive, procedure for assessing land degradation on the basis of an established ecological theory while meeting most of the mentioned requirements for small scale applications. Its adaptation to LADAMER/DeSurvey, requires the method to be upgraded in a number of aspects. The conceptual basis will be adapted to a wider range of climates, vegetation types, and land use settings. The temporal resolution will be increased from mean annual to annual and, possibly, seasonal to better capture the cover changes of deciduous and annual vegetation types or crops. Moreover, the conceptual basis and cartographic modelling procedures will be modified to allow application at a range of spatial resolutions (e.g. 30 m – 1 km). Multivariate regionalisation of the target area, in terms of soil-lithology, terrain and land cover types, is used to reduce uncertainty of the assessment.

The Remote Sensing Component

It is widely accepted that satellite remote sensing offers considerable advantages for land degradation assessments. With a comprehensive spatial coverage it is intrinsically synoptic, and provides objective, repetitive data which contribute to resource assessments and monitoring concepts of environmental conditions in drylands (e.g., Hill et al., 1995; Lacaze et al., 1996). However, only if these observations can be coupled with GIS-based ecological modelling concepts, they may develop their full capacity to be used for modifying and adapting environmental management principles and mitigation strategies.

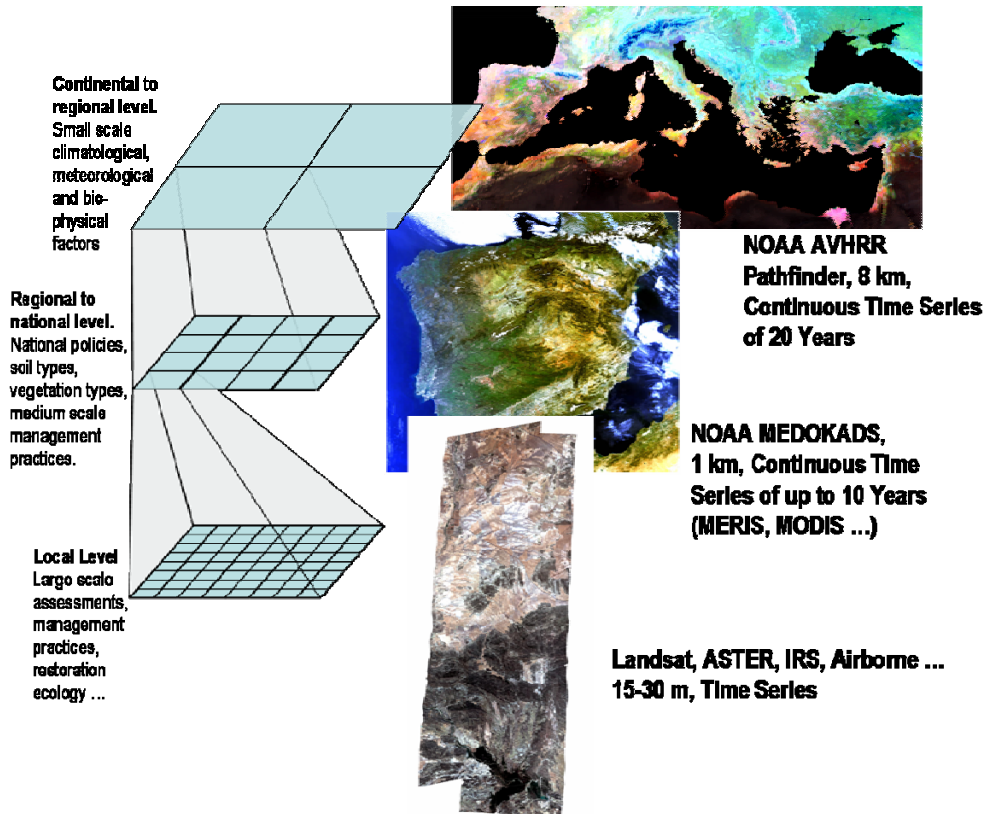


Figure 3. Remote sensing data products covering the range of scales addressed in the LADAMER and DeSurvey projects developed with financial support of the European Commission (DG Research)

It has long been known that surface properties (i.e., vegetation cover and composition, specific properties of parent material and soils) control water availability or the spontaneous emergence and development of new plants in arid and semi-arid regions. Consequently, one of the objectives of remote sensing approaches is to focus on this particular interface. Particularly the application of the ecological assessment framework sketched before requires spatially distributed estimates of the actual vegetation density (i.e. proportional cover), and preferably a set of geo-referenced sample sites were the deviation between actual and potential vegetation density) can be assumed to be minimal. So far, the primary remote sensing input into the model has been limited to spatially distributed estimates of actual vegetation density (either as fractional cover or Leaf Area Index derived in relation to a satellite-based vegetation estimate) which can be derived with reasonable accuracy (e.g. Hostert,

2001). In order to meet the prerequisites of LADAMER, this interface, which so far has been based on limited data series obtained from earth observation satellites (e.g. Landsat TM/ETM, ASTER) must now be extended to accommodate small scale multi-year observations from global monitoring satellites, such as SPOT VEGETATION, NOAA-AVHRR, MODIS, MERIS (figure 3). Therefore, the objective is not only to classify each pixel into land cover based on predefined classification schemes but rather to derive continuous fields of vegetation characteristics at a resolution of 1 km where also sub-pixel heterogeneities of land cover can be considered (e.g., DeFries et al., 1995; Moody & Johnson, 2001; Shababov et al., 2002). A number of techniques have been proposed which also appear suited for a dedicated analysis of multi-year time series of SPOT VEGETATION data that cover the Mediterranean member states of the European Communities. Among these, the most interesting approaches include linear mixture modelling to deconvolve proportional land cover based on spectral or spectro-temporal endmembers, and artificial neural networks which make no assumptions about the linearity of the spectral response to mixtures (e.g., Atkinson et al., 1997). In several Mediterranean ecosystem studies, spectral unmixing techniques have already been successfully used at local scales using high resolution Landsat time series which may facilitate a local validation of the continuous vegetation assessment derived global monitoring satellites (Hostert et al., 2004; Röder et al., 2005).

Changes of the vegetation density over time also bear important information on land degradation dynamics which are induced by natural or man-made processes. In this respect, the production of suitable small-scale map representations of existing degradation trends requires the decoupling of long-term trends and cyclic components of vegetation dynamics (e.g., Moody & Johnson, 2001). Due to the complexity of such approaches, mostly automatic classification or principal-component-related techniques have been employed to global coverage and high temporal resolution imagery for mapping either phenology types or seasonality effects. While these approaches allow identifying pixel clusters with similar temporal and radiometric behaviour, they fail to unveil long-term degradation trends as expressed by associated vegetation changes. In comparison, it has been shown for regions similar to Mediterranean Europe that the first and second harmonics of the discrete Fourier transform concisely summarised the amplitude and phase of annual and biannual signals embedded in time-series of AVHRR-NDVI-data. While this is not yet providing a trend analysis in the classical way, it does constitute information that is of high significance for detecting hot spots of land use changes. The description of regional degradation trends will be further based on a classical trend analysis (parametric and non-parametric) of 20 years of pre-processed 8-km AVHRR Pathfinder data. Major emphasis will be given to novel approaches such as wavelet transforms, singular spectrum analysis, or temporal mixture analysis. Applied to a regional Mediterranean scale the remote sensing component should additionally provide a regional map on which areas of gradual (i.e. long-term) changes can be identified as well as so-called 'hot spots' of abrupt land use change. By coupling trend analysis of vegetation density with the local water balance approach described in the previous objective, we expect to be able to introduce the time dimension in the land degradation assessment. It is important to state that the methodology will be applied at the regional Mediterranean scale, and its performance for monitoring and early warning purposes will be evaluated.

The Land Use / Land Cover Change Modelling Component

The development of integrated assessment models is currently a rapidly expanding activity. This trend is propelled by the growing understanding that policy-making should be based on integrated approaches. System theory clearly has shown that systems and problems do not exist in isolation, rather that they have dimensions that extent into other domains, other disciplines, other levels of detail, and other temporal and spatial scales. Complexity and Computation Theory has shown that even seemingly weak linkages may have major repercussions on the behaviour of the system as a whole. Policy makers, responsible for the management of regions, watersheds, or coastal zones are confronted with this reality on a daily basis. They are to manage fragile systems that exhibit an extremely rich behaviour not in the least because of the many intelligent actors, the human inhabitants or users that steer the development in a direction of their own interest. Confronted with this complexity on the one hand and with better informed, agile recipients of the policies on the other, policy makers have to be able to rely on adequate instruments enabling them to better understand and anticipate the effects of their interventions in the system as fully as possible (e.g., Engelen et al., 1993; 1996). As a result,

today's research and development agendas strongly promote the development of tools enabling an integrated approach, which is propelled by the revolution in the computing hardware and software since the beginning of the eighties. Most relevant in the field of spatial planning and policy making has been the rapid growth of high resolution remote sensing and Geographical Information Systems in the past two decades. As a result new dynamic modelling techniques have been added to the toolbox of the spatial scientists. Agent based approaches, and in particular Cellular Automata, are rapidly gaining interest (e.g., Couclelis, 1997).

Cellular Automata (CA) models can be thought of as simple dynamic systems in which the state of each cell in an n-dimensional array depends on its previous state and on the state of the cells within its neighbourhood, according to a set of stated transition rules. While the early applications of CA models in the spatial sciences remained rather conceptual and theoretical, most recent applications are developed with an aim to realistically represent geographical systems, both in terms of the processes modelled and the geographical detail represented. This trend has come with an increase in the complication of the models developed. One of the very essential relaxations to the standard CA definition is the introduction of the finite non-homogeneous cell space: a bounded cell space consisting of cells having different attribute values representing physical, environmental, social, economic, infrastructural or institutional characteristics of the cell. This has allowed to conceptually and practically link Cellular Automata models with GIS. As a result, most recently, a number of authors have suggested ways to build Cellular Automata functionality into GIS and/or GIS functionality into CA. In this context, remote sensing plays a more than viable role in repeatedly injecting land use information into CA-based land cover change models on various scale levels (e.g. Liverman et al, 1998).

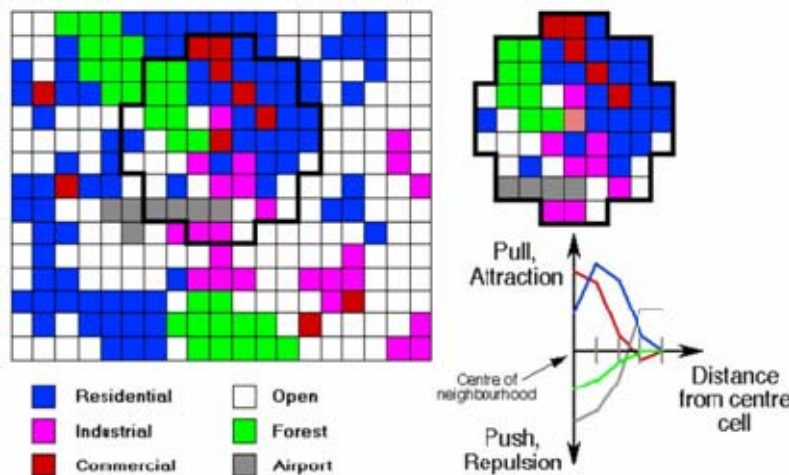


Figure 4. Conceptual aspects of cellular automata (RIKS, Maastricht)

Just as important in the context of integrated modelling are the possibilities for linking CA models to other cellular models representing changes in the cellular space -in which the CA dynamics unfold- or to dynamic models operating at a more macroscopic scale. In the latter case, the macro-models will constrain the overall dynamics of the CA. The models developed, or under development, as part of EU-projects like MODULUS, Medaction, MURBANDY, and MOLAND have taken full advantage of the possibilities to link CA and other dynamic models. In MODULUS this has resulted in an integrated model representing the non-homogeneous character of the cellular space by means of models calculating among other: the soil quality and water balance, the quality and quantity of the aquifer, the characteristics of the natural vegetation. On top of these physical layers (partially also to be derived from remote sensing data), the human dynamics unfold changing the land use and land

cover. These dynamics are governed by CA decision rules, representing human (spatial) behaviour, socio-economic preferences and decision-making, crop choices, etc. This is the basis from which LADAMER will start in its effort to integrate physical, ecological and land use models and apply them to the full Western Mediterranean in an effort to define the 'hot spots' areas prone to desertification. The Integrated Project DeSurvey will follow this line of research and further develop these approaches.

Validation and Methodological Refinements

LADAMER is intended to provide a framework for generating at regional scale information on land degradation status and trends, which allows international and national planners and decision makers to identify those areas where efforts and eventually resources should be concentrated to prevent or mitigate desertification and related land degradation processes. To fulfil this function the information must be reliable and unambiguous, respectively the limitations and uncertainty levels of the methodology must be known. Consequently elements of product validation and uncertainty analyses of the various model parameters and remotely sensed variables are needed. An at least partial validation for the western Mediterranean appears feasible with regard to existing case studies produced in former EU-funded projects. Among these we find the southern Alentejo (DesertLinks, MedAction), the Guadalentin region in SE-Spain (MEDALUS, ERMES, DeMon), Languedoc in S-France (DeMon), Sardinia (GeoRange) and Crete (DeMon); some of these sites will be further investigated within the DeSurvey Project.

GMES and Data User Element of the Earth Observation Envelope Programme

While the integration of remote sensing derived information into ecological process models has triggered widespread applications using medium and high resolution imagery, increasing emphasis is attributed to the synoptic, integrated assessment of larger spatial units, and the provision of dedicated information products for administrations and policy-makers. In the frame of the the European Commission's initiative on Global Monitoring of Environment and Security (GMES), the Ladamer project aims at the small-scale assessment of the degradation status of large areas, and the identification of degradation 'hot spots'. In order to meet these prerequisites, the remote sensing interface, which so far has been based on limited data series obtained from earth observation satellites must now be extended to accommodate small scale multi-year observations from global monitoring satellites; this approach also forms the backbone of the remote sensing component of the recently launched Integrated European Project DeSurvey.

An alternative approach is followed by the DesertWatch project which has recently been launched within the context of the Data User Element of the European Space Agency (ESA) (see also <http://dup.esrin.esa.it/desertwatch/>). This project is primarily triggered to derive land use changes in desertification-affected European countries based on the analysis of Earth observation satellite data from three distinct time steps (1984-1994-2004). Countries affected by desertification are implementing the Convention by developing and carrying out national, sub-regional, and regional action programmes. Criteria for 'preparing these programmes are detailed in the treaty's - five "regional implementation annexes": Africa, Asia, Latin America and the Caribbean, the Central and Eastern Europe and the Northern Mediterranean area (i.e., the Annex IV countries). The DesertWatch project focuses on the latter. In this context, the DesertWatch project addresses the information needs of the national and local authorities of the Annex IV countries of the UNCCD. In particular, the project has been prepared in close collaboration with the national authorities of Italy, Greece, Portugal and Turkey. Its complementarity to the Ladamer Project suggest that both projects should establish linkages to optimise their impact.

Summary

Considering remote sensing and geomatics-oriented approaches, the combined output of the LADAMER and DeSurvey projects should be a comprehensive as well as spatially explicit image of land degradation effects and associated processes for the relevant European Mediterranean countries, in particular for the prototype region of the Iberian Peninsula. It will hence serve as a kind of integrating project between former research approaches and ongoing monitoring and assessment efforts. Consequently, the innovative aspect of LADAMER and DeSurvey lies in the novel combination of optical remote sensing methods with advanced physical, ecological and socio-economic modelling components. Combining these in a surveillance system is expected to substantially improve the quality of land degradation assessment and monitoring at the regional Mediterranean scale. The compiled data base is expected to build a basis for further GMES developments in the domain of land degradation research and other closely connected issues. These aspects will also be further pursued in the Integrated Project DeSurvey which also includes application sites in Northern Africa, Senegal, China and Chile.

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