Integration of Remote Sensing and GIS Techniques in Land Degradation Mapping

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Introduction

Soil degradation processes, as soil erosion by wind and water, physical (compaction, soil structure destruction) and chemical (acidification, salinization/alkalization) deteriorations are increasing at an alarming rate all over the world. The exact definition, quantification and modelling of their regional extent and severity is a rather difficult scientific problem. Soil degradation is not an unavoidable consequence of intensive agriculture and social development. Most of the degradation processes and their unfavourable consequences can be prevented, eliminated, reduced, or at least moderated. Soil degradation is usually a complex process in which several component features of soil deterioration can be recognized to be contributing to the loss of land or its „productive capacity", to the limitation of normal soil functions, and/or the decrease of soil fertility due to unfavourable changes in soil processes and, consequently, in soil properties (FAO, 1979, 1983).

Remote sensing is one of the key tools in monitoring regional environmental processes. An important area of environmental research where the application of satellite imagery can play an important role is soil science, namely the detection of different degradation processes. There have been several initiatives on the application of the information content of satellite images for detecting, mapping and/or monitoring various types of land degradation processes (SKIDMORE et al., 1997). HILL (1993), HILL et al. (1995) reported on the application of remotely sensed images subjected to sophisticated image processing techniques (spectral mixture analysis) for monitoring erosion hazard and changes in vegetation cover in the Mediterranean area. KOK et al. (1995) used NOAA NDVI time series for land degradation studies in Spain. In their work the emphasis was also put on erosion. Salinization/alkalization processes were also studied by the aid of remote sensing. TÓTH et al. (1991) investigated the possibility of using vegetation as an indicator of saline and sodic soil properties in the interpretation of reflectance data resulted from field reflectometry. CSILLAG et al. (1993) and PÁSZTOR & CSILLAG (1995) analyzed discrimination among different salinity states based on high-resolution spectra and identified narrow bands linked to the salinity status of soils. Most recently LENNEY et al. (1996) reported on the applicability of multitemporal NDVI features (derived from Landsat TM images) in mapping the salinity status of agricultural lands in Egypt.

Brief Description of the PHARE MERA Project

The MERA (MARS and Environmental Related Applications) subregional project was launched in 1995 after a long preparation period and the continuous interest and expectations of six Central and Eastern European countries (Bulgaria, Czech Republic, Hungary, Poland, Romania, Slovak Republic). MERA integrates four thematic subprojects: MARS Action 1 (regional inventory), MARS Action 3 (crop yield modelling), Forest Ecosystems Mapping, and Land Degradation Assessment. All of the thematic subprojects fit into the European methodology and knowledge base with the help of the integration factors. The scientific, technical coordination of EC Joint Research Centre ensured that the objectives, the approach and methods used were similar in the relevant subprojects, in each participating country. The remote sensing (and GIS) techniques applied in all subprojects represent another source of integration as well as the common data processing facilities and software provided through the project or made available by the focal points of the project implementation.

In Hungary the FÖMI Remote Sensing Centre was appointed by the Ministry of Agriculture to be the focal point of the implementation of the project. FÖMI RSC performed MARS Action 1, Action 3 subprojects and supported its cooperative partners in their necessary RS and ancillary data processing and analysis, providing them with facilities and expertise. RISSAC and the University of Sopron conducted the thematic and most important analysis tasks in their respective subprojects: Land Degradation and Forest Ecosystems Mapping. The Land Degradation Mapping subproject was implemented by the RISSAC team with the assistance of FÖMI RSC related to the necessary MERA software, hardware and technical support through satellite image analysis and other phases of the project.

The Land Degradation Mapping subproject

The aim of the Land Degradation Mapping subproject was to provide satellite-based land cover maps and digital databases at a regional scale showing the extent of land degradation (soil erosion by water and wind; development of extreme soil reaction [acidification; salinization/alkalization]; physical soil degradation [structure destruction, compaction, surface sealing], extreme moisture

regime [overmoistening, waterlogging, drought sensitivity]; biological degradation [deterioration of soil biota, decrease in soil organic matter]; unfavourable changes in the biogeochemical cycles of elements [especially in the plant nutrient regime, such as leaching, biotic and abiotic immobilization]; decrease in the buffering capacity of soil [soil pollution, toxicity]) in Hungary, and identifying areas that are at risk of land degradation (VÁRALLYAY et al., 1997).
Major tasks of the sub-project:

– Provision of a national map at a scale of 1:500,000, showing the areas of potential and actual soil erosion and other types of land degradation risk.

– Provision of a sample database on land degradation vulnerability for selected representative test areas and for the evaluation of the use of remotely sensed data for the detection and delineation of such areas at the scale of 1:100,000.

The methodology (Figure 1) used in the subproject was based on an integrated geographic information system, incorporating Landsat Thematic Mapper satellite imagery and ancillary data on soils, land cover, climate, topography, etc. Briefly, the methodology involved the identification and delineation of the country's major land degradation risk regions (areas of potential land degradation risk). Within these regions detailed satellite image classification of representative test areas was carried out. Actual land degradation risk was determined by overlaying the land degradation risk regions and the classified land cover. An evaluation of the use of satellite image data (Landsat TM) for regional mapping and modelling of land degradation was made. The methodology had five major stages:

– ancillary database compilation;
– land degradation risk regionalization;
– reference data collection;
– satellite image processing;
– results (output maps, evaluation of the methodology).

The integrated GIS database, central point of the methodology, served as the input to, and received the output from the various subproject stages.

The General Methodology

Ancillary database compilation

A large amount of relevant information has accumulated in Hungary as a result of various soil surveys, analyses and mapping carried out during the last 60 years. Information on soil resources has resulted from these activities on national (1:500,000), regional (1:100,000), farm (1:10,000-1:25,000) and field level (1:5,000-1:10,000). Thematic soil maps were also prepared for the whole country in the scale of 1:25,000 and for 70% of the agricultural area in the scale of 1:10,000 (VÁRALLYAY, 1989b, 1997). In the frame of these studies land

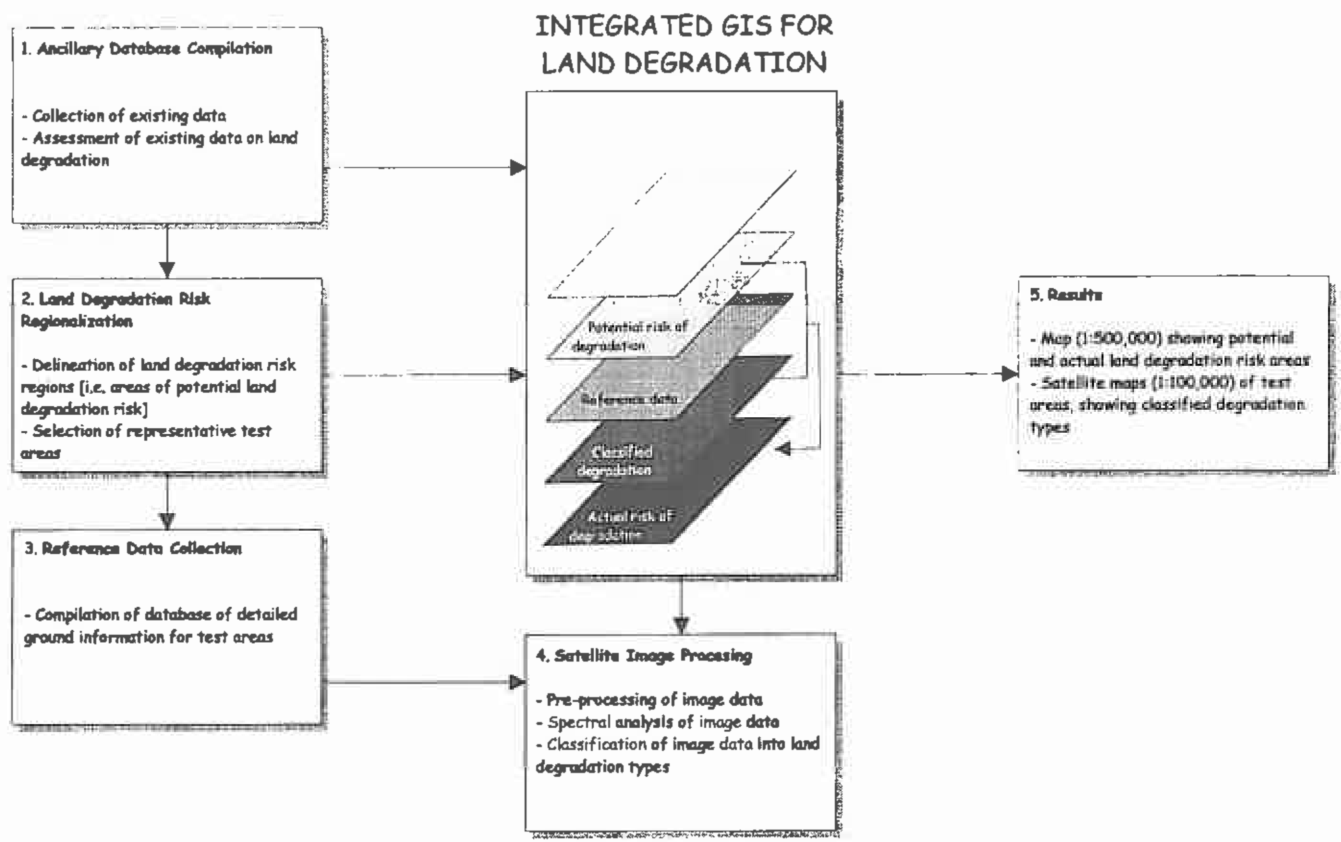

Figure 1
PHARE MERA Land Degradation Mapping Methodology

degradation processes were also thoroughly investigated and mapped (VÁRALLYAY, 1989a). Additionally a great amount of information is available on the various natural factors (climate-weather, surface and subsurface waters, geology, geomorphology, vegetation) as a result of long-term observations, survey and mapping activities (National Atlas, 1989). In accordance with the objectives of the subproject, at this stage merely small scale information (1:100,000 - 1:1,000,000) were taken into consideration.

Many sources were available only in analogue form, consequently, they had to be digitized to enter them into the central GIS database. The following maps (in scale of 1:500,000) were integrated into the system: Genetic soil map of Hungary (Stefanovits & Szücs, 1961), Main types of substance regime of soils (Várallyay, Szücs & Molnár, 1985), Soil erosion (Stefanovits & Duck, 1964), Salt-affected soils (Szabolcs, Várallyay & Mélyvölgyi, 1974) and Susceptibility of soils to physical degradation (Várallyay & Leszták, 1989) (See in VÁRALLYAY, 1989a,b, 1997).

Many of various existing Hungarian soil data were already organized into digital geographic soil information systems by RISSAC GIS LAB. In the present context and scale the AGRO-TOPO and HunSOTER systems provided relevant information. The Agrotopographical System (AGRO-TOPO) is a regional scale (1:100,000) geographical information system developed for Hungary to provide useful information on soils, land use and environmental protection problems. The AGRO-TOPO attribute database file contains information on approx. 4000 geographical units for the whole country. Each soil polygon is considered as a homogeneous agroecological soil unit. The attributes relating to geometrical units are the following: genetic soil types and subtypes according to the Hungarian soil classification (31 categories), parent material (9 categories), soil texture (7 categories), clay mineral composition (10 categories), soil water management (9 categories), soil reaction and carbonate status (5 categories), organic matter resource (6 categories), depth of the column (5 categories), and soil productivity value (bonitation index) (10 categories) (VÁRALLYAY et al., 1985).

Another important information source was provided by the HunSOTER database which is a soil and terrain digital database prepared in the scale of 1:500,000 for the whole country following an international methodology. The database contains (more than 100 different types of) attribute data on the distinguished 1,215 physiographical units, on their terrain and soil components, furthermore on horizons of representative soil profiles linked to soil components. The HunSOTER database is highly suitable for soil degradation studies and modelling of changes in soil characteristics in relation to socio-economic and environmental changes with emphasis on mapping of the vulnerability of soils to degradation or pollution (VÁRALLYAY et al., 1994).

Land degradation risk regionalization

Based on the collected information the following limiting factors of soil fertility and land degradation processes were distinguished and identified:

Extremely coarse texture. – These soils are poor in organic and inorganic colloids, and, consequently, can be characterized by poor water retention, extremely high permeability, low available moisture content, sensitivity against drought and wind erosion, and low natural nutrient content. They can be utilized rationally by a special cropping pattern; their tillage is generally simple, relatively not costly or energy-consumptive. The main possibilities for the reduction of these constraints are the improvement of the extreme moisture and nutrient regimes and preventive measures against wind erosion.

Extremely heavy texture. – Its consequences are: unfavourable physical and hydrophysical properties, poor drainage conditions, extreme moisture regime; unbalanced nutrient regime, retarded root development and nutrient uptake by plants. At the same time extremely heavy texture represents technical difficulties: oversaturation of soils by stagnant surface waters and/or shallow groundwater, problems in mechanized agrotechnics: short periods for tillage operations, particularly for seed-bed preparation, high energy consumption, overcompaction by heavy machinery etc.

Acidity. – In this case, the direct and/or indirect consequences of soil acidity (unfavourable changes in the nutrient regime: fixation, immobilization, ion antagonisms, toxic effects, etc.) limit the nutrient uptake of plants and the microbial activity and unfavourably influence soil structure. Soil acidity can be moderated by liming or by the application of other ameliorants with alkaline reaction.

Salinity-alkalinity. – In various salt affected soils the unfavourable ecological conditions are the consequences of the high water soluble salt content, high Na^+ saturation, strongly alkaline reaction and the unfavourable physical and hydrophysical properties: very low saturated and unsaturated hydraulic conductivity, high water retention, high wilting percentage, limited available moisture content, high rate of swelling and shrinkage, intensive cracking, shallow wetting zone, limited water storage capacity, extreme water regime: waterlogging hazard and drought sensitivity; limited nutrient uptake. The elimination or reduction of these unfavourable properties require complex amelioration technologies: prevention of further Na salt transport to the soil profile; decrease of Na^+ saturation and high alkalinity; improvement of (hydro)physical properties; leaching of accumulated salts from the soil profile and their horizontal transport from the area by drainage.

Salinity-alkalinity in the deeper layers. – This is a permanent potential hazard in poorly drained areas because the rising groundwater (due to a change in climate, land use or water regime) may transport the harmful Na^+ ions from the deeper layers to the active root zone, resulting in serious deterioration.

Erosion. – In strongly or moderately sloping hilly regions soil erosion is the dominant and most important limiting factor of soil productivity and land suitability. The amelioration of eroded lands and the prevention of soil erosion require adequate soil conservation practices, including technical, hydrotechnical and agrotechnical elements.

Shallow depth. – Solid rock, high amount of coarse fragments or cemented horizons can be significant, in some cases drastical limitations for crop production, depending on the character and the depth of the above-mentioned factors. In some places their elimination is possible and necessary, but in most of the cases „shallow soils" can be utilized only by special – usually extensive – land use practices.

Waterlogging. – The rational utilization of permanently or periodically waterlogged territories, swamps, bogs and peats is a special problem not only in agriculture and forestry but in mining activities and environment protection, as well. In low lying, poorly drained topographical depressions, overirrigated areas, floodplain meadows, etc. complex water regulation is the precondition of any further action towards a more rational land use.

The indicated limiting factors cannot be interpreted as absolute (time and space independent) categories because their importance and influence depend greatly on land use, cropping pattern, the given standard of agricultural production, existing system of agrotechnics, etc. If more than one limiting factor exist simultaneously, their relative importance and their partial contribution to the fertility limitation may change. In some cases there are negative or positive causal relationships and interactions among the limiting factors.

Territories affected by various limiting factors of soil fertility were determined by complex queries of the integrated GIS, evaluating the proper influencing factors (grade of water or wind erosion, soil texture, genetic soil type, rootable depth, acidification, depth to groundwater, annual precipitation etc.). Generalizing and merging the maps of individual degradation factors resulted in the compilation of a complex degradation map. To derive the final degradation map and mainly the boundaries of land degradation regions required the consideration of a further information source. The physiographical delineation of the complex land degradation regions became possible by using microregion landscape units. Finally 88 regions were distinguished in Hungary (Figure 2), and were characterized geographically (for details see Land Degradation Mapping Final Report, 1996).

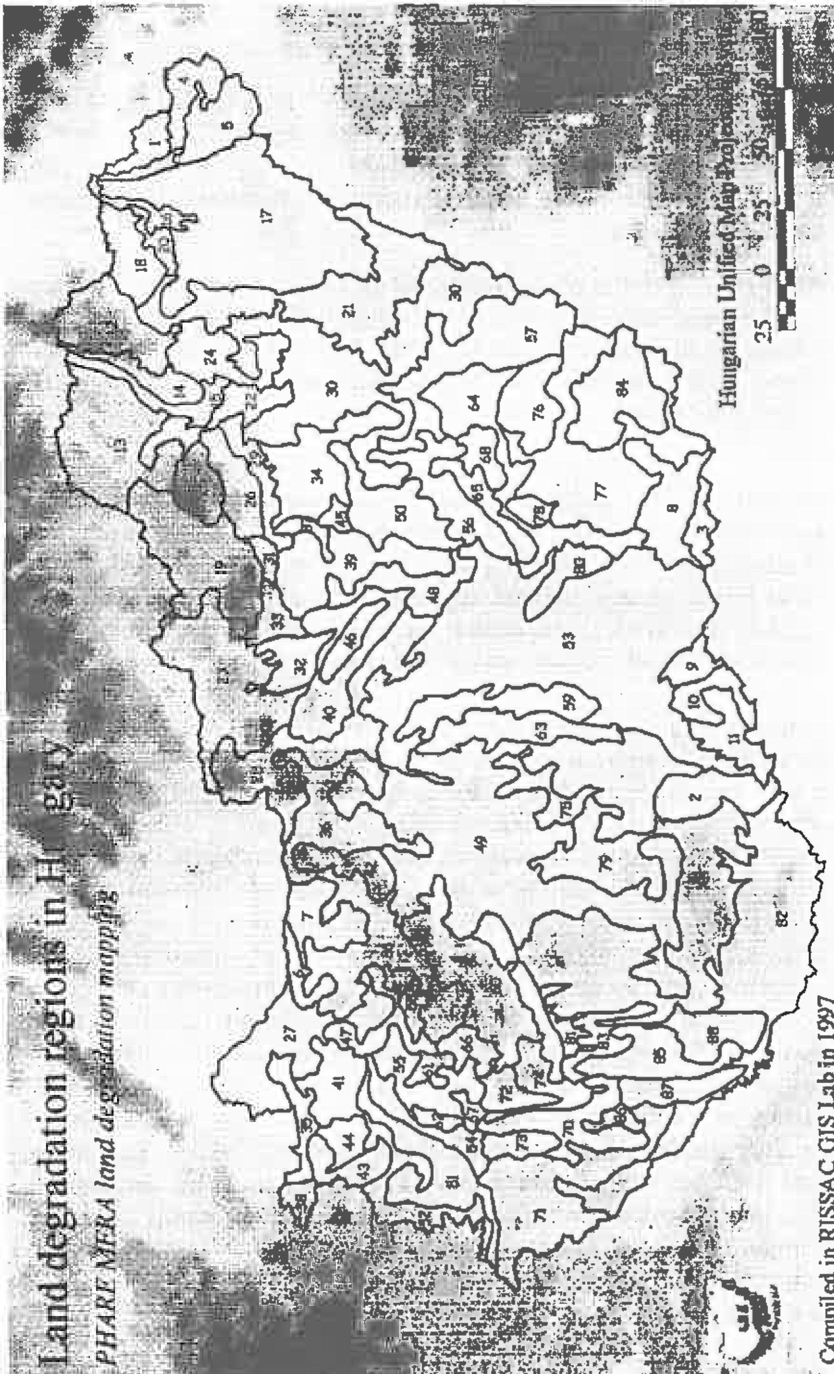

Figure 2
Land degradation regions in Hungary

Reference data collection

Two representative regions have been selected for detailed mapping of two different types of soil degradation processes, at a scale of 1:100,000 using satellite images and image processing methods. These are the (water) erosion and salinization/alkalization regions. The selected test areas represent 64 kmx48 km area each, comprising the size of two CORINE map sheets. The main criteria for the selection of representative test areas within these regions were the following: areas of representative land cover variations within the degradation region; areas located in the most degraded parts of the degradation region; large area coverage within the degradation region; availability of appropriate Landsat TM coverage; availability of updated land cover information from CORINE Land Cover Database; areas covered by one Landsat TM path.

The *„Hortobágy" test area* is located in the salinization/alkalization degradation region covering a significant part of the Hungarian Great Plain Region (including part of the Hortobágy National Conservation Park) in the watershed of the Tisza and Berettyó rivers. The main land cover types of the area consist of alkaline pastures, natural grasslands and cultivated agricultural lands. In the test area the soil formation started on various alluvial sediments and on loess. The alluvium was deposited by the Tisza and its tributaries mainly in the Holocene geological period. Most of the alluvial material is fine-textured (silty clay, clay, heavy clay), non-calcareous and slightly acidic, as a consequence of the mineralogical and chemical composition of the geological formations in the water catchment area and the very low energy (very moderate slope) of the rivers. The loess was partly deposited into dry surfaces of the loess plateaus during the Quaternary period and kept the typical high-porosity features of aeolian deposits. The major part of the loess, however, was deposited into water on waterlogged or moist surfaces of low-lying territories and a considerable part of the loess material was re-deposited, at some places many times, repeatedly by special „lowland erosion" during the later periods. These „lowland loess" and „loess-like" sediments cover extended areas in the Hungarian Plain. Their characteristic properties are: high bulk density, compactness, hydromorphic features (iron mottling; calcium, iron and manganese concretions; gleyic spots, etc.), moderate $CaCO_3$ content and slightly to moderately alkaline reaction.

The *„Mátra" test area* is situated NE from Budapest between the Galgamácsa–Aszód–Hatvan–Jászárokszállás line (S) and the Slovakian border (N), and between the Galga river valley (W) and the Vámosgyörk–Gyöngyös–Cered line through the Mátra mountain (E). The territory consists of undulating surfaces of the Cserhát and Mátra mountains diversified by the Ipoly floodplain (along the Slovakian border) and by the narrow valleys of the Zagyva and Galga rivers and their tributaries, such as Ménes, Dobroda, Tarján, Nógrád and Bér creeks and smaller waterways. According to Stefanovits the „erosion-sensitive days" can be characterized by > 30 mm daily rainfall which may occur 4-

12 times per year. The probability of erosion inducing intense rains is quite high in the test area. The quantity of snow, duration of snow cover and the rate of snow melting show extremely high spatial and time variability. After a cold winter, when the soil is deeply frozen, the quick snow melt may result in intense surface runoff and soil erosion because of limited infiltration due to the impermeable frozen horizon and the limited water storage capacity of the shallow melted topsoil.

Satellite image processing

Satellite image processing and analysis procedures were conducted in two phases using conventional spectral analysis and image classification techniques. Relatively cloud free Landsat TM images were selected from the CORINE land Cover satellite database 1992, comprising of multitemporal and single date image data for the Hortobágy (8 March, 2 May, 21 July 1992) and Mátra (21 July 1992) test areas.

Commonly applied pre-processing steps were implemented on the selected Landsat TM images, including geometric correction and rectification of raw images (HUMPS), preparation of image subsets of the test areas and masking out the settlements from the subimages. Preliminary image analysis steps were addressed to the quality and feasibility assessment of the pre-processed images and reference data set to relate surface element characteristics to the erosion or salinity/alkalinity processes and status of test areas using image enhancement, visual image and GIS analysis techniques on the entire data set. The following procedures were conducted:

– analysis of the relationship between landscape/land use pattern, dominant vegetation cover, surface heterogeneity, field inhomogeneity and degradation processes/status of test areas;

– analysis of spectral and spatial detectability of degraded surface elements according to image acquisition parameters, the spatial scale and spectral separability of data;

- testing and selecting the most suitable subareas, spectral indices, spectral bands and image analysis techniques to be used in the image classification procedures.

Due to the very complex and mixed land use pattern, abundant vegetation cover and types of reference data, some characteristic spectral features of the images (cultivated or natural vegetation cover, difference in cropping pattern, intensity and homogeneity of fields) could only be related to a broad pattern of salinity/alkalinity status in the Hortobágy test area. This resulted the delineation of non or less affected (related to the group of categories 1-4) and strongly affected (related to the group of categories 5-6) subareas on the images. In the latter case, the decrease in intensity and homogeneity of agricultural land use and crop fields could be observed together with the dominance of pasture or natural grassland cover types. However, it was showed that the delineated subareas still represented a mixed degradation status at higher scale (in Landsat TM resolution). This could be further refined, based on the detailed analysis of vegetation cover (type, development) during spectral analysis and image classification procedures utilizing the multitemporal data set.

The main approach was to derive the detailed land use pattern discriminating the agricultural crops and natural vegetation types and to detect additional spectral features (inhomogeneities within agricultural fields, special vegetation association/land use pattern or degraded crop development) related to the salinity/alkalinity status, using the following procedures:

– stratification of the test area into agricultural and non-agricultural (Hortobágy) strata;

– spectral analysis, training and preliminary classification of strata into crop types using isodata clustering, MLH classification techniques on multiband and multidate image data set;

– construction and spectral enhancement of multitemporal NDVI image;

– isodata clustering of multitemporal NDVI image;

– analysis of the NDVI temporal profiles of spectral clusters (20);

– merging and labelling spectral clusters into land use/vegetation type thematic classes in association with their salinity/alkalinity status, where it was possible.

More detailed land use pattern (discriminating main agricultural crops, pastures, forests, water) and some degraded areas representing very low NDVI values or field inhomogeneities could be revealed on the test area but could not be related efficiently to the underlying alkalinity/salinity status in the agricultural (Nagykunság) stratum at larger scale using clustering or MLH classification techniques. The most efficient classification results were achieved in the non-agricultural (Hortobágy) stratum using the multitemporal NDVI composite image with clustering and temporal profile analysis methods. In the final vegetation map, it was possible to delineate 5 land cover classes that could be associated with the salinity/alkalinity status on the grassland area. These are the grassy saline „puszta" and Artemisia saline „puszta" (salt affected), the „marsh" (less salt affected) and the „loess steppe" (non salt affected) vegetation classes. However, to resolve some confusion and mixing effect in the classification map and to assess its accuracy quantitatively, other techniques and a more extended and detailed reference data set need to be applied in the future.

Conclusions

Summary of the results

Identification, delineation and description of the country's major land degradation regions (areas of potential land degradation risk) at 1:500,000 scale were accomplished by building and analysing an extended digital land degradation geographic database. Based on this result the evaluation of further mapping and analysis of the erosion and salinization/alkalinization degradation processes in two test areas (Mátra and Hortobágy) were conducted using a compiled reference data set, Landsat TM images, image classification and GIS analysis techniques, respectively at 1:100,000 and larger scale. After conducting image pre-processing and preliminary image analysis steps on each test area, the stratification of the Hortobágy test area and the application of isodata clustering and temporal profile analysis of multitemporal NDVI image were implemented efficiently. It showed encouraging results to detect various land cover types and even discriminate subclasses in the grassland area related to the salinity/alkalinity status.

Evaluation of the methodology

Based on the achieved results GIS analysis techniques can be used successfully to delineate potential land degradation risk areas at regional level. The conventional multitemporal satellite image analysis method can also be applied efficiently to derive the land cover map for representative sub areas of degraded lands, showing the extent and level of salinity/alkalinity status of a stratum dominated by natural grassland vegetation. Incorporating more detailed field reference data, more homogeneous spectral signatures or other ancillary data into the image classification procedure (image segmentation, textural band) may result better discrimination between the surface elements and vegetation development status in this spectrally mixed and complex environment.

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