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## **ECOSYSTEMIC APPROACHES TO LAND DEGRADATION**

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### **ABSTRACT**

Land degradation is recognized as the main outcome of desertification. However available procedures for its assessment are still unsatisfactory because are often too costly for surveying large areas and rely on specific components of the degradation process without being able to integrate them in a unique process. One of the objectives of DeSurvey project is designing and implementing operational procedures for desertification surveillance, including land degradation. A strategic report was compiled and reproduced here for selecting the most appropriate approaches to the project conditions. The report focuses on using attributes of ecosystem maturity as a natural way to integrate the different drivers of land degradation in simple indices. The review surveys different families of attributes concerned with water and energy fluxes through the ecosystem, its capacity to sustain biomass and net primary productivity, and its capacity to structure the space. Finally, some conclusions are presented about the choice criteria of the different approaches in the frame of operational applications.

### **1. INTRODUCTION**

The land degradation concept aims at covering a range of climatic and man induced processes that lead to a decline of the soil potential to sustain plant productivity. The first attempt to produce a global assessment occurred at the end of the last century, resulting in a 'Global Assessment of Soil Degradation' (GLASOD 1988-1990). GLASOD was a qualitative assessment, largely based on expert judgement that distinguished the main processes and drivers leading to soil degradation, such as water and wind erosion-sedimentation, soil and water salinisation, loss of soil organic carbon and soil nutrients, loss of soil structure, etc. GLASOD data were used in the preparation of the World Atlas of Desertification, published by UNEP in collaboration with some national and international institutions.

GLASOD approach was recently upgraded by a new worldwide project 'Land Degradation Assessment in Drylands' (LADA-2002) sponsored by UNEP, GEF and FAO. While retaining the original GLASOD categories of soil degradation, LADA takes a step forward by (i) attempting at delivering quantitative results, (ii) formally including socio-economic drivers and (iii) enlarging its scope to carbon balances and biodiversity as components of the functional land system and its degradation process.

A third global initiative with implications in land degradation assessment is the 'Millennium Ecosystem Assessment' (MA). Its report 'Desertification Synthesis' is already available. It evaluates the condition of desertification in drylands, by asking pointed questions and providing

answers based exclusively on the reports generated for the MA. It provides a consistent picture of the links between land degradation, climate change and biodiversity loss. It also supplies guidelines for improving assessment and monitoring approaches taking into account the role of human actions and climate variability.

The three afore-mentioned projects reveal an historical trend of increasing complexity in land degradation assessment approaches. They go from ‘soil’ to ‘land’, from considering effects to explicitly include drivers (climate variability and human activity) and to be more concerned with global interactions of desertification (climate change, biodiversity).

This trend has been largely driven by the UNCCD definition of desertification (United Nations 1994) as ‘*the land degradation in arid and semi-arid and dry-sub-humid areas resulting from various factors, including climatic variations and human activities*’. This definition, in spite of its generality and simplicity has the advantage of providing a benchmark for designing assessment and diagnostic methods. The outcome or symptom of desertification is *land degradation*, and its driving forces are *climatic variations* and *human activities*. Furthermore land degradation is defined by UNCCD as a ‘*loss of land’s biological and economic productivity and complexity*’. This is a holistic definition that looks at the bulked impact rather than at the particular causes, like soil erosion, salinisation, etc.

The DeSurvey is the last newcomer of the efforts in this line. Its objective is to develop and implement a cost-efficient procedure for assessing and monitoring of land degradation status and trend over large areas in an appropriate format to provide a link to the ‘land suitability’ attribute that is used classically used by economists to allocate land use changes in space.

By retaining the holistic characteristic of the land degradation concept, we propose to focus on an ecosystemic approach rather than the original from UNCCD definition, which includes human drivers. This way fits better to the ‘biophysical’ set of drivers, while the economic constraints are provided by the interaction with the socio-economic forcing. In the following we’ll use ‘land condition’ as a more general term than land degradation. The latter represents the degraded extreme of the land condition range.

There are several ecosystem attributes which association to the ecosystem degree of ‘maturity’ or ‘complexity’ is widely recognised. On this background, landscape’s long-term capacity to retain, utilise and recycle local resources, and to buffer environmental changes provides an objective basis for assessing its ecological functionality or condition.

Procedures based on this kind of approach are relatively unsophisticated and provide process-based indices that work by measuring the deviation of the land condition status of a particular target cell from a reference for the non-degraded condition. They are therefore little data demanding, low cost, little prone to error propagation and well suited to be implemented on remotely sensed time series of data for application to large areas.

## 2. ECOSYSTEM ATTRIBUTES ASSOCIATED TO LAND CONDITION

There are several families of attributes that can be related to the degree of ecosystem maturity and hence, of land condition. In the following we provide an overview such attributes, including short comments on their functional characteristics and assumptions to be used as land condition indices, approaches to their determination, data requirements and constraints to their application.

### Hydrological ratios

*Assumption.* The more degraded an area is, the less its capacity to channel its water inputs, like rainfall (P) into the evapotranspiration flux ( $ET_a$ ). As a consequence the ratio  $ET_a/P$  (evapotranspiration index) will be low compared to non degraded areas.

*Approach.* It is required to obtain spatially distributed estimates of  $ET_a$ , P in both, target areas and regional references for non degraded areas. Long term annual  $ET_a$  estimates

will be obtained from local deviations of vegetation density from regional reference values (Specht 1972, Boer 1999, Boer & Puigdefabregas 2005, Boer & Puigdefabregas 2003, Zhang *et al* 2001, Arora 2002). It is often assumed that these reference sites have unlimited soil moisture storage capacity, and vegetation canopies have constant water vapour conductance values during the year, which have evolved as to transpire as much as possible without full exhaustion of water in the dry season.

Data requirements.

- Time series of monthly values of precipitation and temperatures
- DEMs
- Remotely sensed vegetation density surrogates (i.e. NDVI) covering an annual cycle (ideally monthly images during 4-5 years, minimum 6 images in an annual cycle).
- Land use maps, at least discriminating agricultural, urban and rangelands & forest areas.
- Ancillary information as lithological / soil maps is helpful but not mandatory.

Constraints.

- Quality of estimates depend (i) from the availability of regional reference cases for low degradation level, (ii) from the coherence of the different information layers in terms of geo-reference and resolution, and (iii) from the number and representativity of the NDVI data sets.
- These models perform better at high spatial resolution ( $\leq 100$  m). At lower resolutions, the uncertainty increases.
- The assumptions of unlimited soil water storage capacity and constant canopy conductance of water vapour for reference agraded vegetation might not hold in some cases. This could be particularly true if potential vegetation in hydrological equilibrium does not occur in the target area, and not evergreen vegetation cover.

General comment. Although these methods require a considerable sophistication in GIS and spatial modelling, the underlying core models are relatively simple, they include a small number of parameters and are little data demanding (most of them are available from public sources). As a consequence, the risks of error propagation are minimized.

## Energy ratios

Assumption. The ratio of sensible heat flux ( $H$ ) to latent heat flux ( $LE$ ) or evaporation in energy terms is the Bowen ratio ( $H/LE$ ). It is expected to increase along the land degradation gradient because the poorer and thinner is the soil, and the less is vegetation density, the larger will be sensible heat over latent heat.

Approach. Remotely-sensed estimates of  $H$  and even more  $LE$ , are costly and prone to errors because they are not straight derived from remotely sensed data (Kustas & Norman 1996, Chehbouni *et al* 1997, Bastiaansen *et al* 1998). In order to minimise these drawbacks, there are two options available.

1. Starting from the energy balance equation:  $Rn-G = LE+H$ . Being,  $Rn$  net radiation,  $G$  soil heat flux and  $R-G = available\ energy$ . Most authors assume that daily soil heat fluxes ( $G$ ) are zero. Therefore we can take the sensible heat fraction ( $H/Rn$ ) as a land degradation index equivalent but more operational than  $H/LE$  (García *et al* 2005).
2. A further simplification, to reduce the intermediate errors, can be achieved by working the ratio  $SVI/LST$ , where  $SVI$  refers to vegetation density

indices (i.e. *NDVI*) and *LST* to radiometric land surface temperature (*LST*). Vegetation density and *LST* may be taken as surrogates for *LE* and *H* respectively. This approach has been adopted for other purposes, such as soil moisture assessment (Sandholt et al 2002) or identification of vegetation and land use types (Lambin & Ehrlich 1996) but could easily be adapted to land degradation assessment.

Data requirements.

- Time series of monthly values of precipitation and temperatures
- DEMs
- Remotely sensed radiometric temperatures and vegetation density surrogates (i.e. *NDVI*) covering an annual cycle (ideally monthly images during 4-5 years, minimum 6 images in an annual cycle).
- Land use maps, at least discriminating agricultural, urban and rangelands & forest areas.
- Ancillary information as lithological / soil maps is helpful but not mandatory.

Constraints. Not to be applied at high spatial resolutions. Typically operational radiometric temperature sensors work at resolutions  $\geq 1$  km.

General comments. It is an attractive attribute that can be approached in a straightforward and self contained way. Very promising for low resolution applications. It will be implemented in the project on the basis of previous research on land use discrimination and change (Lambin & Ehrlich 1996) and soil moisture assessment (Sandholt et al 2002).

## **Biomass and Productivity**

Assumption. The reduction of plant biomass and net primary productivity (NPP) below of non desertified land on equivalent environmental conditions is proportional to the experienced land degradation. This is the most widespread perception of desertification and the most related with UNCCD definition. Both biomass and NPP can be reasonably estimated using satellite-derived information (Prince & Justice 1991). Two ecosystem attributes are relevant for this assessment: annual average biomass and seasonal or inter-annual peaks. The former shows the ecosystem capacity to long term sustain biomass, while the latter concerns its resilience to recover from disturbances, namely rainfall fluctuations (Pickup et al 1994). It may be expected that average annual biomass and NPP decreases along land degradation gradients while peak NPP (resilience) is low in both very degraded and agraded conditions, and is maximum at intermediate degradation values. Similarly seasonal NPP peaks are expected to perform better as land degradation indices.

Approach.

Two families of approaches have been proposed for assessing land degradation in drylands using satellite data. Both are based on the rainfall use efficiency concept (RUE). In the direct approach, efficiency is explicitly related to NPP, while in the indirect method remotely sensed vegetation density is used as a surrogate for NPP.

*Direct RUE (NPP/P).* Estimates of NPP are obtained using a carbon cycle model (GLO-PEM) that uses satellite data (Prince and Goward 1995, Prince 2002). GLO-PEM relies on physiological principles to model the amount of carbon fixed per unit of absorbed photosynthetically active radiation (APAR), which depends on the incident photosynthetically active radiation (PAR) and the spectral vegetation index (SVI) value. APAR yields gross primary

production (GPP) by applying a conversion efficiency, which is estimated using stress factors related to plant physiological control (i.e. air temperature, vapour pressure deficit, soil moisture). Respiration related to growth and maintenance of biomass is subtracted from GPP to obtain NPP. In drylands, NPP is directly related to rainfall, therefore direct RUE (NPP/P) provides a useful index of degradation in terms of its deviation from the potential value in the climatic condition of the target area.

*Indirect RUE (SVI/P).* Annual averages and maximum peaks of vegetation density (SVI) are taken as surrogates for annual biomass and peak biomass growth respectively. RUE is calculated as the ratio of these SCIs to annual rainfall and previous 6-months rainfall respectively (del Barrio et al. 2005).

The two afore described RUE indices are related to the concept of rainfall use efficiency defined by Le Houerou (1984). This author showed, through local terrain studies, that RUE decreases in degraded lands.

Actual RUE values need to be expressed in relation to their potential counterparts at the same climatic conditions. Typically this is empirically achieved by plotting the observations in the RUE / AI space. Where AI (aridity index) =  $E_o / P$ .  $E_o$  is annual mean evapotranspiration and P is annual mean rainfall. In the case of direct RUE index, a model-based approach to estimate potential NPP has been proposed, as a way to take into account factors other than rainfall that may also control NPP such as soils, nutrients and heterotrophic respiration (Prince 2002). To this purpose a comprehensive biogeochemical model (CEVSA) has been developed (Cao and Woodward 1998).

#### Data requirements.

3. Time series of monthly values of precipitation and temperatures (only indirect RUE, direct RUE can obtain this information from satellite data).
4. DEMs
5. Remotely sensed vegetation density surrogates (i.e. NDVI) covering an annual cycle (ideally monthly images during 4-5 years, minimum 6 images in an annual cycle). (Direct RUE needs full data sets from the AVHRR images and also from TOMS (Total Ozone Mapping Spectrometer) to obtain ultraviolet observations of cloud cover).
6. Land use & Land cover maps, at least discriminating agricultural, urban and rangelands & forest areas, are helpful but not mandatory except for direct RUE and CEVSA.
7. Ancillary information as lithological / soil maps is helpful but not mandatory except for direct RUE and CEVSA.

Constraints. Direct RUE indices are mostly designed to low resolution applications (typically < 8 km) and outputs are largely dependent on complex modelling assumptions with uncontrolled uncertainty. In the case of Direct RUE indices, quality of estimates depend (i) from the availability of regional reference cases for low degradation level, (ii) from the coherence of the different information layers in terms of geo-reference and resolution, and (iii) from the time coverage and representativity of the SVI data sets.

General comment. Direct RUE approaches yield quantitative direct estimates of ecosystem processes related to land degradation, such as NPP and biomass changes, but are more prone to uncontrolled errors and unable to work at medium/high spatial resolutions. Indirect RUE indices are more simple and robust and can perform well at high spatial resolution, but outputs are less intuitive.

## Spatial patterns

*Assumption.* The spatial structure of some key landscape attributes change with the progress of land degradation. This change may be shown in terms of the range (grain) of the landscape mosaic and of its pattern intensity (between patch heterogeneity). For example, the effects of terrain and soil spatial heterogeneity on the spatial structure of vegetation cover are expected to be more expressed in degraded than in non degraded areas.

*Approach.* Comparing the spatial structure of landscape key attributes in the target areas to reference non degraded areas. SVI is often used as attribute, but other high level indices, such as those described in afore sections may be employed as well.

*Data requirements.* Single or representative time averaged satellite-derived SVI or other chosen attribute are required, together with their corresponding DEMs and climatic data sets. Soil / lithological maps are also helpful but not mandatory.

*Constraints.* Spatial structure is scale dependent and therefore most enhanced results are obtained when these methods are applied through a range of spatial resolutions.

*General comment.* These methods are attractive, straightforward and little demanding in terms of parameters and intermediate assumptions. They may be particularly suited to drylands with combinations of sparse and aggregated vegetation. However they are still on development within the project. Similar approaches have been applied in gentle relief areas of Australian rangelands (Pickup et al. 1994) very different from those prevailing in the Mediterranean region.

### 3. GUIDELINES TO SELECT OF INDICES FOR LAND CONDITION ASSESSMENT.

When it is intended to work at medium/high spatial resolutions (<1km) to detect relatively slow changes in land condition (i.e. time intervals of 5y – 10y between snapshots). These snapshots should be averages of 5-10 years as to minimize noise. Therefore the indices to be selected for the final procedure should meet the following requirements:

- Modelling complexity to transform raw satellite data into variables to be included in the indices should be kept at minimum levels. Otherwise the accumulation of errors could affect the sensibility of the method to discriminate spatial and temporal differences in the assessment.
- Basic data involved in the index calculation should come from Earth Observation Systems and standardised information (climatic and terrain –DEM). Other data with poorer standardisation, geo-positioning and scaling procedures (i.e. soil data, land use / cover) should be avoided in the index core.
- All indices should be scaled to their potential values at their climatic conditions. Consequently procedures for estimating potential values along the aridity index gradient should be described and feasible.
- Validation of the algorithm underlying the selected indices should be feasible. This does not refer to its performance as land condition indicator, which has to be achieved through external parallel assessments.

Screening out the land degradation indices reviewed in Section 2 after the afore stated selection criteria, the following could be discarded from the set considered of interest to work in the afore-stated conditions.

- Hydrological ratios: They are likely more suited to high spatial resolution ( $\geq 100\text{m}$ ) as to reproduce the most relevant topographic features at the hillslope-

channel scale. However their performance at coarser resolutions is doubtful. Their assumptions for the most agrated reference sites might be unrealistic (i.e. non-limited soil water holding capacity, constant evapotranspiration conductance of the land surface during the year as an adaptation to use the maximum soil water without exhausting its storage).

- Energy ratios, option 1 (H/Rn): Too much complexity in the calculation of H makes this approach prone to error accumulation. Discarding soil G (soil-atmosphere energy diurnal net flux) can be held only around the equinoxes, but not in winter and summer.
- Biomass and productivity, Direct RUE (NPP/P): NPP calculation is based on rather complex models, which rely on physiological information and external data (i.e. land cover). The uncertainty of the outputs risks to be large, particularly at medium-high spatial resolutions ( $\leq 1$ km), which are those to be used in DeSurvey.

Therefore the proposed indices to be retained are:

- Energy ratios, option 2 (SVI/LST).
- Biomass and Productivity, Indirect RUE (SVI/P).
- Spatial patterns.

It is recommended to explore further the complementarity of the three approaches and the environmental conditions best suited for the application of each of them.

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