Strategy for the Dynamic Study of Desertification

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Abstract

The experience of a large project ongoing in Tunisia is used to discuss the different aspects of desertification monitoring with the help of remote sensing. Emphasis is put on performing appropriate field measurements by surface sampling for satellite data calibration. Change detection is linked to simple surface parameters such as brightness, green vegetation cover and soil color. Soil surface optical properties are dominant in the signal received by the satellites and show strong potential for long term degradation detection. Long time series of Landsat MSS data can be used to detect these surface changes over the last 20 years. As a result of the real-size test done in Tunisia a global methodology for a satellite-based arid land monitoring strategy is proposed for further discussion and development.

Résumé

A partir de l'expérience acquise au cours du projet « Veille Satellitaire de la Désertification en Tunisie méridionale » différents aspects de l'utilisation de la télédétection pour le suivi des milieux arides sont discutés. Le premier est la nécessité d'avoir des mesures de terrain basées sur un échantillonnage des différents types de surfaces. Ensuite, la détection des changements est basée sur des paramètres simples tels la brillance, le couvert végétal et la couleur du sol. Les propriétés optiques de la surface des sols sont dominantes dans le signal reçu par les satellites, elles montrent un fort potentiel pour la détection des phénomènes de dégradation à long terme. Des séries d'images Landsat MSS permettent ainsi de suivre les changements de ces surfaces au cours des 20 dernières années. A partir de cette expérience une stratégie pour le suivi à long terme des régions arides est proposée à la discussion et pour de futurs développements.

Introduction

The word desertification is largely used nowadays, but it may encompass very different phenomena such as: climatic changes at different scales of time, decrease of vegetation cover, sand movement, soil erosion, population depletion,... Numerous publications can be found discussing definitions of desertification as discussed in the reviews of VERSTRAETE (1986), and MAINGUET (1991) for instance. However, progressively a consensus has emerged and a commonly agreed definition, proposed by UNEP in 1991, has finally been adopted by UNCED in 1992.

Based on this background, this paper refers to *arid land degradation resulting mainly from adverse human impact*. More precisely, the present study deals with the use of remote sensing techniques for assessing the extent and intensity of land degradation as well as the impact of actions undertaken to combat it. Namely, arid lands are not only suffering degradation but are also treated for restoration and rehabilitation (see ARONSON *et al.*, 1993).

The approach described has been developed within a desertification monitoring project currently carried out in Tunisia. It is more than just a concept, it is a real-size feasibility test for a long term satellite-based « land degradation watch » program in the arid and semi-arid parts of the Mediterranean region.

Climatic crisis, as severe drought or strong storms, can reveal and/or accelerate ongoing degradation processes. Population movements are also often related to land degradation, an increased human pressure can induce degradation, whereas degraded lands may be depopulated. These aspects will not be discussed here, the focus is primarily on monitoring evidences of desertification. The questions addressed are: is land degradation occurring, at what intensity, speed and extent, are the treated areas recovering better condition,... These facts need to be clearly established before further investigating causes and consequences.

Desertification symptoms

In the steppes of the northern fringe of the Sahara land degradation phenomena induced by harming practices like cultivation of sandy soils and overgrazing have been intensively studied by field ecologists. As a result characteristic degradation sequences have been described (FLORET et PONTANIER, 1982). Typically, during the degradation process of arid ecosystems of this region the perennial vegetation cover decreases whereas the upper part of the soil is eroded by wind and/or water. In other parts of the landscape sand deposits will build sterile dunes (Fig. 1).

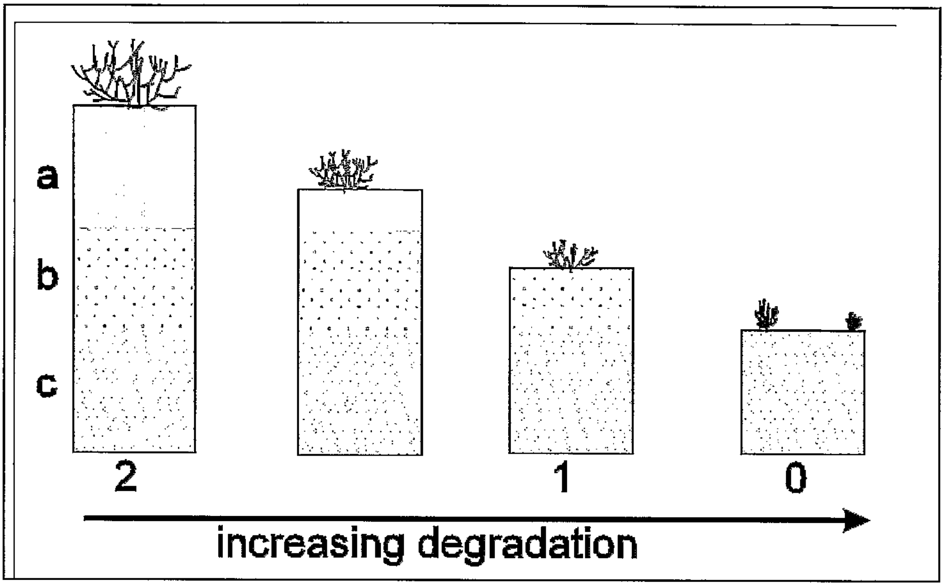

Figure 1. Typical degradation sequence of a sandy steppe of southern Tunisia (adapted from FLORET et PONTANIER, 1982). The different soil materials (from A to C) are progressively eroded whereas the steppic vegetation cover diminishes under overgrazing. The different status : non degraded, degraded and very degraded are labeled 2, 1 and 0, respectively (see comments further in the text).

Figure 1. Séquence de dégradation typique d'une steppe sableuse du Sud tunisien (adapté de FLORET et PONTANIER, 1982). Les différents horizons pédologiques (de A à C) sont progressivement érodés alors que le couvert végétal diminue par surpâturage. Les différents états : non dégradé, dégradé et très dégradé sont repérés par les chiffres 2, 1 et 0 respectivement (voir dans le texte).

Among the symptoms of land degradation in this area, several are easy to determine in the ground:

- Change in plant species;
- Diminution of vegetation cover;
- Soil surface sealing;
- Thinning and removal of topsoil;
- Decrease in water infiltration and storage in soils;
- Decrease of biological activity;
- Sand mobilization;
- Mobile sand deposition;
- Soil salinisation.

On the contrary, the restoration of degraded areas will be characterized by :

- Increase of vegetation cover;
- Sand stabilization and fixation;
- Increase of water infiltration and storage in soils;

- Increase of biological activity.

A given area can be subjected to strong fluctuations of any of these parameters, accentuated by climatic variability. A monitoring effort is needed to discriminate short term "noise" from long term trends.

Monitoring needs

In order to assess the status of a given area, i.e. degraded, stable or improved, the changes should be measured by comparison with previous stages taken as reference. In other words the modifications undergone by vegetation and soils have to be monitored. This can be done at different scales. A coarse assessment of land status at a continental level is of interest for global environmental studies, typically climatic change modeling. But this is of very little relevance for a land degradation control program. In this case a precise geographical positioning of the areas suffering degradation is needed as well as detailed maps for action plans (implementation of sand fixation barriers, gullies treatment, e.g.).

Such a detailed mapping effort is very costly and time consuming if only based on field investigations. From this respect remote sensing appears as a powerful tool providing regularly "snapshots" of the aspect of land surface, potentially covering large areas cost-efficiently. Indeed several studies have already demonstrated the significance of satellite data for arid environment studies, including in the African Sahel (see the review of PRINCE *et al.*, 1990) and in Tunisia (ESCADAFAL, 1989).

A satellite-based desertification monitoring program needs to access to some kind of historical archive to have the reference situations from which changes over time will be detected. Combined with he need for high resolution data, this leads to selecting optical sensor data among the currently available remote sensing imagery, i.e. Landsat MSS and TM, SPOT (Table 1). When archive of more recent sensors data will have been build they will also be usable for monitoring purposes (see conclusion).

Table 1. Currently available satellite data for long term, high resolution land surface monitoring programs.

Tableau 1. Données satellitaires actuellement disponibles pour le suivi à long terme.

Platform	Sensor	Archive span	Bands *	Resolution	Periodicity
Landsat (1 to 5)	MSS	22 years	3 VIS, 1 PIR	80x80 m	18 days
Landsat (4,5)	TM	12 years	3 VIS, 2 NIR, 2 MIR	30x30 m	16 days
SPOT (1 to 3)	XS	9 years	2 VIS, 1 NIR	20x20 m	26 days
SPOT (1 to 3)	Panchro	9 years	1 VIS	10x10 m	26 days

* Spectral range: VIS: visible, NIR: near infrared, MIR: medium infrared.

What can be remotely sensed ?

Remote sensing data are primarily images in which patterns characteristic of certain components of arid landscapes can appear such as field boundaries, tree plantations,... But besides these limited situations it is generally not possible to recognize directly the objects we are interested in. Only the analysis of the numbers behind each picture element can give us some of the information we need. These numbers are measurements of the intensity of the light reflected by the land surface. Sensors perform these measurements in different parts of the spectrum (see spectral ranges of table 1), leading to the concept of spectral signature whereby objects with specific spectral features can be identified -such as green vegetation or red soils- (GUYOT, 1989).

In the studied areas, the changes with time in energy reflected by the target viewed by the sensors depend principally on modifications of: vegetation type, abundance and phenology, soil surface composition, structure and humidity (ESCADAFAL et GIRARD, 1993).

Landsat and SPOT satellites acquire imagery regularly, with an approximately monthly rate, at a constant solar time (the exact temporal pattern varies with the platform, see table 1). Under mid-latitudes this means the images are acquired throughout the year with different solar elevations. One of the main remote sensing feature of a steppic landscape is the impact of shadows on the signal, like the one created by bushy vegetation. The geometry of the sun - target - sensor system must then be taken into consideration when selecting images for changes detection. Typically a long term study should use a set of images recorded at the same periods of the year (for similar sun elevation) over the maximum of time span available (Table 1).

Even in the case of series of images acquired with similar geometrical configuration, fluctuations of atmosphere composition hinder a direct comparison of these data. These atmospheric effects have to be corrected before differences between images can be computed and attributed to land surface changes (DESCHAMPS *et al.*, 1981).

A field based methodology.

Concept : detecting change in soil surface composition and structure

One of the most widely spread use of remote sensing data for desertification monitoring has been the detection of variations of the green vegetation cover. This approach is adapted to the savannas of the African Sahel (TUCKER *et al.*, 1985) but not well suited to the north Sahara steppes with woody plants, mostly non-green chamaephytes.

In the approach developed here the whole soil surface is considered in its global function of bio-geosphere / atmosphere interface. All the different components are taken account and a soil surface sample is considered as a mosaic of basic or surface subunits, such as vegetation clump, sandy layer, surface crusted soil, litter covered soil, (ESCADAFAL, 1981, 1989). Figure 2 illustrates this hierarchical approach used to describe the whole land surface instead of just a specific element such as vegetation cover or soil type.

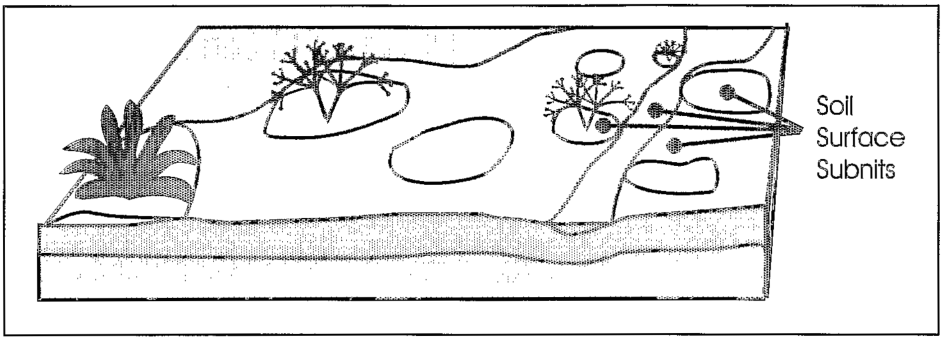

Figure 2. Heterogeneous surfaces can be characterized as mosaic of simpler homogeneous surface subunits (adapted from ESCADAFAL, 1981). *Measuring the properties and extent of each subunit allows to compute average values for complex surfaces.*

Figure 2. Les surfaces hétérogènes sont considérées comme des mosaïques de sous-unités homogènes (« états de surfaces élementaires », adapté de ESCADAFAL, 1981). *La mesure de l'extension et des propriétés de chaque sous-unité permet de calculer des valeurs moyennes de la surface complexe.*

Changes in the land condition induce modifications of the type and/or distribution of the different surface subunits, which can be characterized by simple field observation techniques. To these modifications are related alterations of the biotic potential, of the water infiltration capability, as well as of the seedling emergence possibilities, as shown in the Sahel (CASENAVE et VALENTIN, 1989) and in Tunisia (ESCADAFAL, 1989).

These very same modifications of the land surface also change the way incoming light is reflected. This has two main impacts :

- Modifications of the energy balance and linked potential climatic effects, which are beyond the scope of this paper,

- Modifications of the signal received by remote sensing satellites, which is the basis of the methodology developed. Theoretically all changes visible in the ground are detectable in visible bands sensor data, provided they cover a large enough area. Among these, color changes are related to important soil properties and recent works detail the techniques for remote sensing of soil surface color (ESCADAFAL *et al.*, 1989; ESCADAFAL, 1993).

Characterization of soil surface spectral signatures

In the studied areas, the different degradation levels of each of the main ecosystems correspond to surface conditions well described in the field. To assess how they can be remotely sensed, their spectral signatures have to be investigated. This has been done by field spectroradiometry campaigns described in details elsewhere (ESCADAFAL *et al.* 1994). With this technique a collection of spectral signatures (reflectance spectra) has been established for the different elementary surface subunits encountered (corresponding to soils and plants in various conditions, from "good" to "very degraded"). All this information is stored in a computerized database to allow easy access.

In the case of complex surfaces, i.e. composed of different surface subunits, an overall spectral reflectance can be computed using the average of the reflectances of each subunit, weighted by their relative extent.

First results : degraded land spectral signature

Computed from reflectance spectra recorded over soil and vegetation of the degradation sequence cited above, reflectance values in the Landsat TM and SPOT XS bands have been reported in table 2.

Table 2. Reflectance values for vegetation and soils of the degradation sequence (Landsat-TM and SPOT-XS bands).

Tableau 2. Valeur de réflectance pour la végétation et les sols de la séquence de dégradation étudiée (bandes Landsat-TM et SPOT-XS.

	Very degraded soil (0)*	Degraded soil (1)*	Non degraded soil (2)*	Green vegetation	Non green vegetation (woody)
TM1	36.39	19.35	18.1	12.76	7.28
TM2	51.21	33.6	34.89	18.28	9.6
TM3	62.32	45.15	49.89	21.57	11.69
TM4	71.65	52.15	59.42	41.07	15.69
XS1	48.27	30.37	30.97	17.24	9.14
XS2	61.57	44.54	49.07	21.53	11.53
XS3	71.64	52.15	59.41	41.1	15.7

* see Figure 1.

In order to evaluate the contribution of soil and vegetation in the overall surface spectral properties a simple model has been used. Reflectance values of the three types of soils are linearly combined with those of the two types of vegetation at three different cover levels using the simple equation:

$$\rho_v = a \cdot \rho_v + (1-a) \cdot \rho_s$$

where:

ρ = surface reflectance,

ρ_v = vegetation reflectance,

ρ_s = soil reflectance

a = vegetation fraction cover

In this rough model the shadows are neglected assuming measurements are made when the sun is close to zenith. Table 3 summarizes the different combinations used in this model. The number symbolizes the soil status, whereas the letter specifies the vegetation type and cover.

Table 3. Symbols for the combinations of soil and vegetation used in the linear model (these symbols are used in the following discussion).

Tableau 3. Symboles utilisés pour les combinaisons de sol et de végération utilisées dans le modèle linéaire (la discussion y fait référence).

	0% vegetation (bare soil)	10% green vegetation v	20% green vegetation V	10% woody vegetation s	20% woody vegetation S
Very degraded soil: **0**	0	0v	0V	0s	0S
Degraded soil: **1**	1	1v	1V	1s	1S
Non degraded soil: **2**	2	2v	2V	2s	2S

Change detection

Intercalibration of satellite data

In order to transfer the field results to satellite data, it is necessary to make image data comparable with ground reflectances. Several techniques can be used, in this project we have developed a very pragmatic and robust approach base on pseudo-invariant surfaces (CASELLES *et al.*, 1989) . Large land surface parts such as stony slopes, sand dune fields are used as calibration references. Their spectral signature has been measured in the ground during the field campaigns, it has been observed that there is little seasonal variation because of the very limited vegetation cover. The only source of reflectance variation is water content, which is usually very low because of the dry climate. The reflectance is modified only during a few hours after a storm, these events are monitored by the meteorological services and images recorded in wet surface conditions will not be used in the invariants correction technique.

After geometric correction and registration over a topographic map, the radiance values (in digital numbers) in the image corresponding to the invariant zones are retrieved. A linear regression allow then to convert the image radiance values into reflectance values. This process tends to eliminate satellite sensor drift as well as first order atmospheric effects. It is even possible to intercalibrate images from different sensors, using the ground collected spectra and the transmission function of the instruments (ESCADAFAL *et al.*, 1993).

These operations of geometrical registration and radiometrical rectification allow then to stack up series of images for change computation. Although civilian satellite based remote sensing started in 1972 with the MSS sensor on the Landsat series, it is not easy to build a well documented archive of images over Africa. Most of the images which have not been used after acquisition by the operators have not been stored for further use (this does not apply to USA and Canada). However, series of 12 to 15 images between 1972 and 1993 have been prepared over each of our three test areas with the help of the EROS Data Center (USA) and Eurimage (Italy).

Such multitemporal data sets have a large dimensionality of n (number of dates) times c (number of channels). They can be processed with a classical statistical approach by performing a principal component analysis to reduce the dimensionality. But the resulting decorrelated new channels are difficult to interpret thematically (FERRARI, 1992).

Use of simple band combinations (indices)

In the current project we developed a different approach based on detecting changes in indices values, simple linear combinations of bands of known thematic significance.

Whereas raw measurements such as the surface radiances in a specific wavelength have no particular meaning for the ecologist and cannot be used as is, more usable indices can be derived from satellite images. Indices have the advantage of being a fast and easy first step of data processing, which is not strongly altering the information content of the original data, while eliminating some of the remaining noise related to differences in atmosphere and instrument calibration between dates.

Considering the current satellites mentioned above, their sensors have in common three bands providing measurements in the following spectral domains:
- "Green" band: Landsat MSS4, Landsat TM2 and SPOT XS1;
- "Red" band: Landsat MSS5, Landsat TM3 and SPOT XS2;
- "Near infra-red" band: Landsat MSS7, Landsat TM4 and SPOT XS3.

Three types of indices can be obtained by linear combinations of measurements in these bands : *Brightness index, Vegetation index and Color Index*

Several *brightness indices* can be found in the literature, as a suggestion the following general formulation can be used:

$$BI = \sqrt{G^2 + R^2 + IR^2}$$

Among the various *vegetation indices*, whereas the most widespread NDVI is sensitive to soil noise, the SAVI proposed by HUETE (1988) is eliminating a significant amount of the soil effect while remaining very simple to compute:

$$NDVI = \frac{IR - R}{IR + R}$$

$$SAVI = \frac{IR - R}{IR + R + l} \cdot (1 + l) \text{ where } l = 0.5$$

Several color indices have been recently developed (ESCADAFAL, 1993), by definition they are limited to the visible spectral range, i.e. here the two bands R and G. Globally soil surface color changes are due to the presence of more ore less reddish soil materials

(ESCADAFAL *et al.*, 1989). The simple normalized difference between the two bands expresses the "redness" of the surface (*Redness Index*, ESCADAFAL and HUETE, 1991a):

$$RI = \frac{R-G}{R+G}$$

Although the data in channels R and G are generally correlated, this index has already been applied successfully for soil surface discrimination in arid lands (ESCADAFAL and POUGET, 1989). Other more sophisticated color indices have been developed for satellites with three visible bands such as Landsat TM (ESCADAFAL *et al.*, 1994).

Table 4. Indices values obtained for the soil-vegetation combinations depicted in table 3.

Tableau 4. Valeurs des indices obtenues pour les combinaisons sols-végétation décrites dans le tableau 3.

	NDVI			Brightness			Redness		
	0	*1*	*2*	*0*	*1*	*2*	*0*	*1*	*2*
0	0.07	0.07	0.09	55.3	37.5	40.5	0.42	0.57	0.64
v	0.08	0.09	0.10	52.2	36.1	38.8	0.42	0.56	0.63
V	0.09	0.11	0.12	49.0	34.7	37.1	0.42	0.55	0.61
s	0.07	0.07	0.09	50.9	34.9	37.6	0.42	0.57	0.63
S	0.08	0.09	0.10	46.5	32.2	34.6	0.41	0.53	0.59

Table 4 shows the values obtained for these different indices in the soil/vegetation combinations tested. Several striking features appear clearly:

- Brightness shows a large variation range, increasing while vegetation cover decreases. But this is not a sufficient criteria as brightness varies also strongly with soil type, for instance it decreases from non-degraded (2) to degraded soil (1). Besides, brightness is known to be highly sensitive to shadowing and angular effects, whereas ratio-based indices are less sensitive (ESCADAFAL and HUETE, 1991b).

- The NDVI range is very narrow and NDVI is very sensitive to soil background as already shown for other arid soils of Arizona (ESCADAFAL et HUETE 1991a). This index is here unable to detect the different vegetation levels (Fig. 3), as experienced by KENNEDY (1989) with NOAA-AVHRR data over Tunisia.

- The redness index, RI, is clearly expressing the soil degradation level, independently of the vegetation type and abundance (Fig. 4). The signal is much stronger as the range of values observed is very wide compared to those of the NDVI. But this might not be a general rule. However it shows strong potential in association with brightness.

As conclusion these first results of the field campaigns, the data show a high variation of soil related indices with degradation status, whereas the classical vegetation index is not usable. These results are currently under application to the imagery over the area (time series).

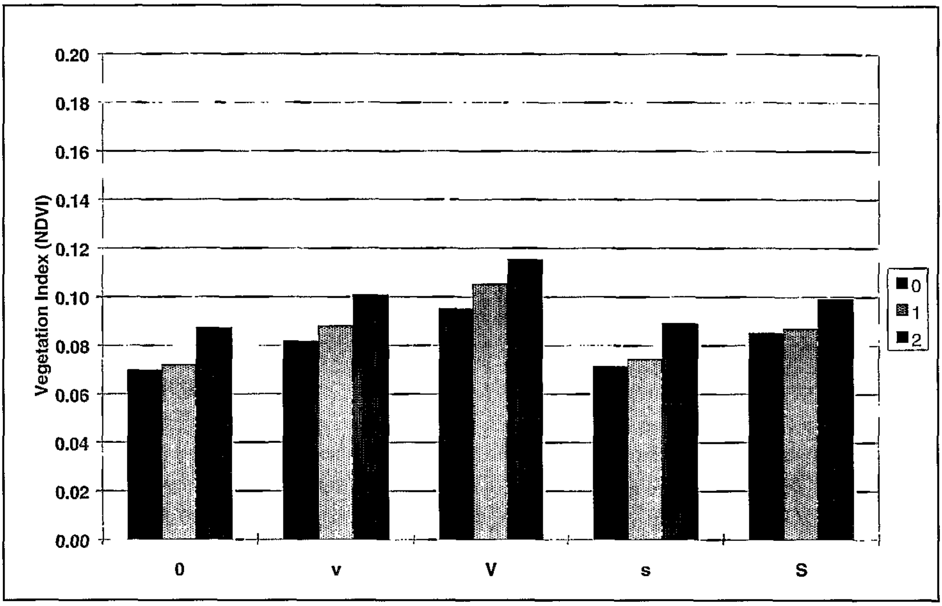

Figure 3. Vegetation index values (NDVI) obtained for various degradation situations simulated from field radiometric data (see Table 3 for symbols, in each 3 columns from left to right: soil status 0, 1 and 2).

Figure 3. Valeurs de l'indice de végétation obtenues pour les différents états de dégradation, simulées à partir de mesures radiométriques de terrain (voir le Tableau 3 pour la signification des symboles, dans chaque groupe de colonnes de gauche à droite: états du sol 0, 1 et 2).

Viewing ground and satellite information in perspective

In the approach developed, satellite derived "index images" are produced, this technique can evidence surface changes (with spatial extension and intensity). But then ecologists and other "field-based-knowledge" specialists have to input their expertise to interpret this brightness, color, or vegetation index changes within the context of local land surface processes (Fig. 5).

As an example of the significance of field experience, in the studied test area, a decrease in redness index corresponds to the thinning of the superficial sandy soil layer. In this case this leads to a lowering of water intake and seedling emergence capabilities of the soil, indicating undergoing desertification (ESCADAFAL *et al.*, 1994). In other areas, the interpretation of higher redness index values might just be opposite: erosion of the organic topsoil exposing the lower layers of a red Mediterranean soil, for instance.

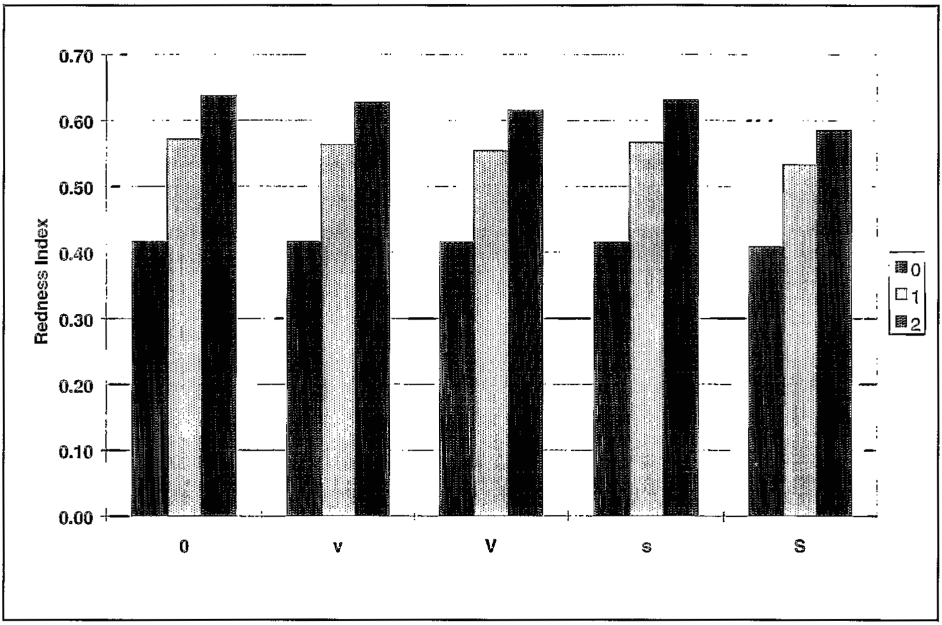

Figure 4. Color index values (redness index, RI) obtained for various degradation situations simulated from field radiometric data (see Fig 3 for details).

Figure 4. Valeurs de l'indice de coloration obtenues pour les différents états de dégradation, simulées à partir de mesures radiométriques de terrain (voir les détails dans la figure 3).

This discussion demonstrates that *there is no such a thing as a "desertification index"* directly obtained from satellite data (although "drought indices" have been developed from meteorological satellites data, but drought is only one of the possible causes, whereas we are here looking at evidences of land degradation). Only *soil surface condition indices* can be derived from satellites, which changes can be interpreted in terms of desertification by specialists having a fair knowledge of what is on the ground.

Moreover, the interpretation of these indices changes might vary in time with increasing knowledge and experience. But the facts will remain : a land surface change measured from space (intensity and extension) remains the same piece of information whatever the interpretation of this information should be.

As a result, the constitution of an archive of well calibrated and geometrically corrected indices imagery might be the best use of Landsat and SPOT data for land degradation monitoring.

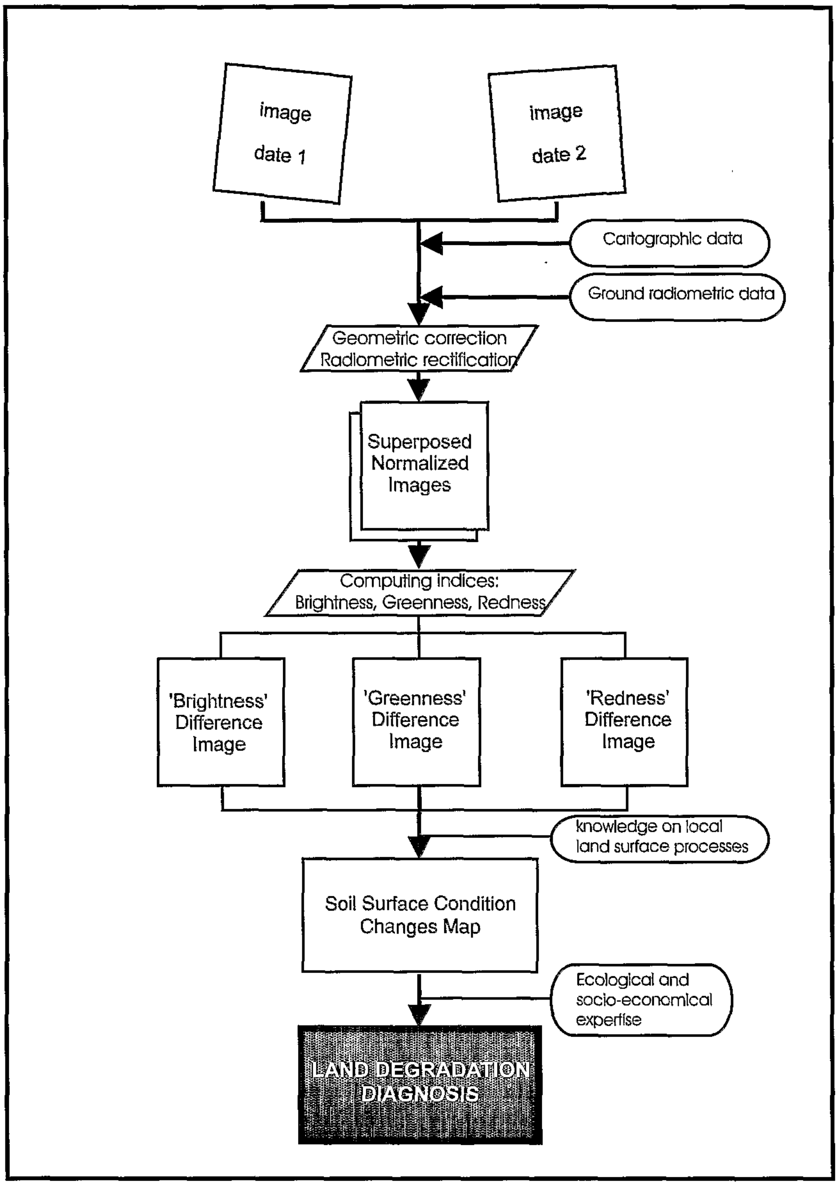

Figure 5. Flow diagram of the methodology developed for desertification monitoring in Tunisia. *Ground data and field expertise is imputed throughout the process.*

Figure 5. Organigramme de la méthode développée pour le suivi de la désertification en Tunisie. *Des données de terrain et de l'expertise sur le milieu sont introduites à différentes étapes du processus.*

Conclusion - prospective

The approach currently used

The program described here can be summarized as "land surface satellite monitoring for arid land status (degradation and restoration)". It is based on simple and robust techniques, to build up a whole data processing chain from ground characterization to regional mapping of desertification. The first results show the importance of soils in the signal received by the satellites. Generally speaking, compared to vegetation cover changes, soil surface changes are likely to be slower phenomena indicating *long term trends.*

The cost efficiency cannot yet be established, but as this project is a real size test, an evaluation of this type will be possible at the end, as well as the connection with socio-economic data.

Future developments

Among the undergoing refinements of the data processing, spectral mixture modeling applied to series of Landsat TM images is one of the most promising for our purpose.

In this approach, when transforming the data, instead of statistically based axis which are image dependent, the axis can be defined by pixel populations corresponding to "pure" scene components such as woody vegetation, green vegetation, grey rocks, reddish soil, white sand,... These pure components must have unique spectral signatures, thus high band number is needed. Each pixel is then redefined in the new data space. At the end of the computing process the observed signature of a given pixel is "unmixed" into specific amounts of each pure components (HILL and MEGIER, 1991).

As in any satellite based monitoring program the new technologies such as the future hyperspectral sensors and medium resolution imagery of the environmental programs (MERIS, MODIS) will bring a better picture. Time series of new instruments such as ERS1 SAR will also give new insights.

But the biggest challenge is probably to use the existing data, collected in the last two decades by different sources, stored in different agencies under different formats. The exploitation of this somehow hidden but very large amount of information would help tremendously to assess the changes undergoing in the Mediterranean environment by bringing a unified and regional view which seems currently lacking.

Acknowledgements

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