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A MEASURING REFERENCE SYSTEM TO QUANTIFY THE DESERTIFICATION PROCESS IN A SEMIARID ECOSYSTEM BASED ON LANDSAT MSS DATA

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ABSTRACT

Desertification -the degrading effect of man's activities on land productivity- is one of the major processes contributing to global ecological deterioration. Despite its recognized worldwide importance, no reliable measure of desertification exists today that can be economically applied on a synoptic scale. Ground-based observations are expensive and inefficient.

Data gathered with the Landsat MSS system are used to make a quantitative evaluation of the state and rate of change of desertification in four data sets gathered by Landsat during a nine-year old period, over a 3600 km^2 semiarid test site in the state of San Luis Potosi México.

A systems methodology is used to characterize a semiarid ecosystem as a set of target systems. Structural and behavioral modalities of the target systems are used to identify the general system type. It was established that the target system could be studied as a macro-deterministic system.

Two observable indicators in Landsat data are used to derive a model for quantifying desertification: the mean albedo and the mean information content of the target systems.

Three experiments were performed to verify the logic and coherence of the state variables proposed with the model. The first experiment simulated the process of desertification in a target system. The simulation was made on one image by displacing a window of 64x64 pixels in succesive steps from a uniformly vegetated area (not altered) to a desertified (strongly altered) area.

The general trend of behavior expected in the state variables was observed in 6 of 9 simulations. Two additional indicators of information content were tested, and the expected behavior was observed in all 9 simulations.

In the second experiment a set of 64x64 pixel windows, randomly chosen within the test site, were observed for 4 different times. It was found that by ordering the windows with the values of each of the state variables analyzed, the same order was observed for the 4 different times.

The third experiment demonstrated the potential capability of the model to measure the state and advance of desertification. Graphics are presented of the trajectories observed in selected windows within specific measurement levels for 4 different times. An example of an information system for environmental monitoring is presented.

I. INTRODUCTION

Desertification -the degrading effect of man's activities on land productivity- is one of the major processes contributing to global ecological deterioration. Despite its recognized importance (UNCOD, 1977; Anaya, 1983, p.131) no unique measure of desertification exists today that can be economically applied on a synoptic scale. Ground based observations are expensive and inefficient.

The purpose of this study was to determine to what extent Landsat MSS radiometric measurements could be used as indicators of the process of desertification, and could provide the basis for a system to monitor the process from space.

II. BACKGROUND

The study of desertification using Landsat MSS digital data has been based on two different strategies. Some investigators (Hellden et al., 1980, 1982; De Carvalho and Lombardo, 1980) consider that supervised classifications using training fields of different degrees of desertification can give satisfactory results. This approach has several inherent limitations when applied operationally. The training fields are usually selected on the basis of "indicators" observed during field visits which are usually far below the geometric level of resolution of the Landsat MSS. Our early attempts to correlate field observations of indicators of desertification (e.g. presence/ absence of vegetation types, grazing and overgrazing, soil types, etc.) with Landsat data were unsuccessful.

Other investigators have simplified the study of desertification by measuring only one terrain attribute (see Robinove et al.,1981; Otterman,1974, 1981; Coiner, 1980; Warren and Hutchinson,1980; Robinson,1984; Frank,1984). This simplification has often produced more useful and less costly results than the supervised classification techniques.

The development and use of vegetation indices has been frequently proposed as a more direct method of measuring desertification. Nevertheless, it has been found that sparse or low levels of vegetation cover (30%) can be seldom spectrally detected (Mouat and Hutchinson, 1983, p.104). Graetz and Gentle (1982) have proposed that an index of shadowing effects of low vegetation and grasses in semi-arid grazing lands could be used in areas with 30% vegetation cover. Otterman (1981) and Warren & Huthinson (1980) have suggested that the organic materials covering the soil could be more significant than the vegetative cover in measuring desertification with Landsat MSS data. Robinove et al. (1981) proposed the use of albedo as an important and measurable indicator of desertification using Landsat MSS data. This idea is based on the supposition that, as vegetation and organic materials are removed by different means, these changes result in an increase in the reflected energy in the spectral range of the Landsat system. De la Torre (1984) has confirmed that the use of albedo is more effective than vegetation indices in semi-arid environments.

Coiner (1980) and Robinson (1982) proposed three indicators derived from the statistical properties of Landsat MSS data to detect changes in vegetation induced by the processes of desertification. They found that the correlation of MSS band 5 with MSS band 7 was a sensitive indicator of change in vegetative cover for a unit or cell within the image.

Dalsted and Myers (1983, p.64) contend that desertification has many differents forms of manifestation, dependent on the region under study. They propose the use of Landsat MSS images to regionalize the geographic space (mapping units) and the description of the risk of desertification in each mapping unit based on various terrain attributes. This approach implies extensive field work and can be very costly. Additionally, the time involved in such extensive mapping can negate the value of Landsat data for satisfying demands for timely information.

III. DESERTIFICATION AS AN INVERSE PROBLEM

Robinove (1983) has indicated that radiometric measurements made by the Landsat MSS system are secondary indicators of terrain attributes, and should be used with caution when used for mapping purposes.

Mapping the state and advance of desertification requires the selection of a set of descriptive vectors. The problem of which (or how many) vectors should be used must be resolved by the observer, usually in terms of his objectives and available resources.

It is assumed that a measurement of two or more descriptors will provide more information than the use of only one descriptor. The basic problem is to determine to what extent Landsat MSS radiometric measurements can be related, directly or indirectly, with attributes judged adequate to measure desertification. Vemuri (1978, p.61) has indicated that this type of problem can be considered as an inverse problem (Figure 1). In other words, we are observing the system output at different moments in time, and must deduce the system operation from these observations.

IV. THE SEMIARID TEST SITE

A. LOCATION

The test site was located in the western part of the state of San Lúis Potosí, México, between parallels 22° 45'N and

23°22'N, and meridians 101°21'W (1024 x 1024 pixels). The site falls within the central plateau physiographic province, the second most populated province in the country.

At the regional level it is considered to be a very homogeneus unit in terms of soil, climate and topography. This was considered to be beneficial inasmuch as changes could be attributed to desertification phenomena instead of geographic variations within the area.

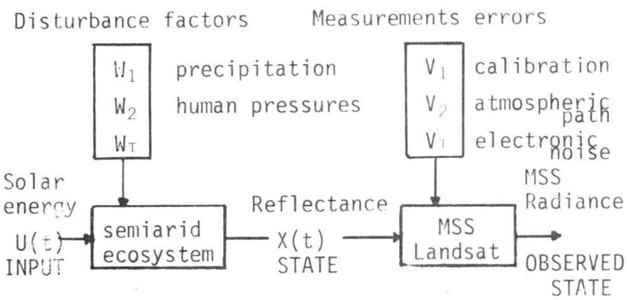

Figure 1. Desertification as an inverse problem.

B. THE SEMIARID ECOSYSTEM

One of the principal characteristics of semiarid ecosystems is low rainfall. Water has become the most important controlling factor in the biological processes (Noy-Mier, 1973). This type of ecosystem is known as a "water-controlled system".

While temperature, solar radiation and input nutrients of the system vary continuously throughout the year, rainfall occurs discontinuously in packets. The biological response of the system or of any of its parts to the event "water" is a "pulse" (Figure 2). When sufficient water enters the system, the biological processes are activated and the ecosystem responds with a pulse of biomass production. As the water available is used, the biological processes decrease to their stable state, called the "zero-state". Periods of drought are usually more extended than periods of growth and production of biomass, and results in a pulse-stabilized system. These pulses may occur seasonally, as in the test site (Figure 2a) or may be randomly distributed throughout the year (Figure 2b). Studies of the

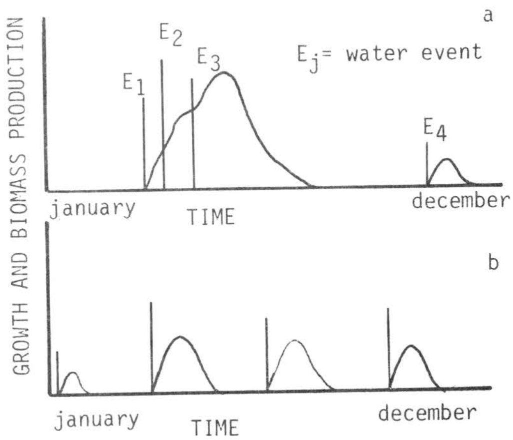

Figure 2. Rain patterns in semi-arid ecosystems. a = stationary b = random.

available meteorological records (10years) in the test area indicated that the zero-state would most likely occur in the month of March in any given year, and selection of data sets during that time period would enable us to avoid fluctuations due to random and seasonal rainfall-induced pulses.

According to Sutherland (1976) the system of interest to us can be classified as a finite state macro-deterministic system despite its stochastic response at the micro level. We assumed that measurements of the system in the zero-state would allow us to detect changes and the direction of changes in the state of the system due to desertification factors and not to dynamic features of the system itself.

V. A PROPOSED MODEL TO MEASURE THE DESERTIFICATION PROCESS

What we perceive as changes in surface features of any landscape are always differences perceived at some level of resolution. Subtle changes which could be observed by an ecologist in the field would normally not be perceptible in satellite images. Those changes that we do observe are major transformations in the landscape such as development of new cultivated area, construction of roads and highways, the construction or expansion of human settlements, large areas subjected to erosional processes, etc. Robinson (1982) has called these transformations "first-order changes".

Changes in albedo can be used as an indirect indicator to observe changes in vegetative or organic cover, and can serve as one element in a descriptive vector of change. The use of albedo as a unique linear indicator of landscape degradation has inherent limitations. Removal of natural vegetative cover in an ecosystem and its conversion to agriculture may or may not be considered a type of degradation. When the structural and functional homeostasis of an ecosystem is destroyed and substituted by a monoculture it can be more productive than its original state, but from an ecological point of view the system has been simplified and disturbed. Albedo measurements in this case would lead us to the conclusion that all land should be cultivated. In a semi-arid ecosystem in particular this type of "improvement" is usually short-lived.

It is proposed that the mean information content of a subset of pixels (cell) be used as an indirect measure of ordering in the landscape and as a second element in the descriptive vector of desertification.

The reference model proposed to quantify the state and advance of desertification is shown in Figure 3. Four regions or classes of landuse are proposed, only one of which is considered "desertified". In this ideal model the albedo varies from 0 to 100%, and the information content from 0 to 4.8 bits (an artificial constraint imposed by our ability to classify a maximum of 60 classes of information). The curve assumes that a cell in a naturally ecologically balanced state will exhibit homogeneous properties initially, pass through a disturbed state exhibiting many classes, and end once more in a homogeneous state, but desertified with high albedo.

VI. DATA AND PROCEDURES

A. DATA

Four of five available Landsat images (Table 1) were used in the study. The image of March 20, 1976, was rejected because of excessive line drop-out and noise in all bands.

Table 1. Characteristics of the Landsat images used in this study.

Identifier	Landsat	Solar ∢	Date
8123816451500	1	50°	March 18,1973
8533616050500	1	50°	March 20,1976
82191216222X0	2	44°	March 14,1979
82225016310X0	2	48°	March 21,1981
82255616311X0	2	34°	January21,1982

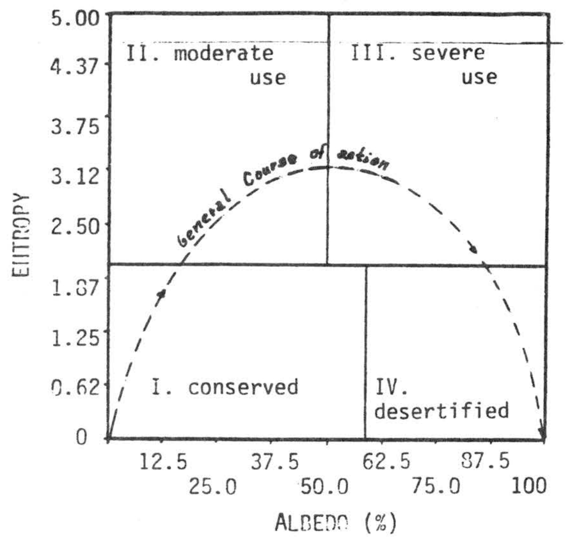

Figure 3. Schematic representation of the total set of states of desertification and its relation to four categories of desertification.

B. PROCEDURES

The test site area (1024 x 1024 pixels) was divided into 256 (64 x 64 pixel)cells. The state variables mean albedo (A) and mean information content (H) were calculated for each cell, for each data set.

The albedo of each cell was calculated by use of equation (1) proposed by Otterman (quoted by Robinove, 1981, p.140 The mean was determined by the sum of the albedo values in the cell divided by the number of pixels in the cell.

$$\text{ALBEDO (A)} = \frac{\pi}{I \cdot \text{sen}\,\alpha}\left[\frac{B_4}{G_4}+\frac{B_5}{G_5}+\frac{B_6}{G_6}+\frac{B_7}{G_7}\right] \quad (1)$$

where: I = total solar irradiance in the four bands = 70.13 mW/cm^2
α = sun angle from the horizontal
B_i= digital value of pixel in band i
G_i= gain in digital counts per unit radiance (from the calibration of the multispectral scanner).

The mean information content (entropy) was calculated by the use of equation (2), proposed by Shannon (quoted by Rubinstein, 1975, p.171). The events considered are the spectral classes derived from an unsupervised classification of the pixels within each cell.

$$\text{ENTROPY} = H = \sum_{i=1}^{n} P(E_i)\log_2 \frac{1}{P(E_i)} \qquad (2)$$

where: E_i = spectral class i within the cell

All digital processing was performed on the digital image processing system of the Dirección General de Geografía DGG, utilizing the "ELAS" software of the Earth Resources Laboratory (ERL/NASA 1980).

Three experiments were made to confirm the utility of the proposed model of desertification.

The Bulldozer Experiment. The bulldozer experiment was conceived as a possible method of supporting the model of desertification. We imagined a large semiarid area covered by natural vegetation (homogeneous at the resolution of Landsat) which we could "bulldoze" and incrementally strip of vegetation. If we could make periodic observations and calculations of the variables "H" and "A" during this artificially produced desertification process, the results should be similar to those predicted by the general model proposed.

An alternative, and less costly and destructive, solution was devised by selecting a "window" within a Landsat image and moving the window in successive steps from a uniformly vegetated area to a more desertified area. Though the obvious defect of this method would be that the final window of the bulldozer would not be of the same area as the original window, it was equally obvious that the data would represent less desertified to more desertified conditions. A schematic diagram of this process is shown in Figure 4.

Figure 5 shows the results of the first bulldozer simulation performed with a 64 x 64 pixel window of data acquired by Landsat in 1979. The curve obtained was quite encouraging for its similarity to that predicted by the model. An adjustment of the curve to a quadratic function resulted in a coefficient of determination of R^2=0.88. Though these indications seemed favorable, only five of nine such simulations produced favorable results.

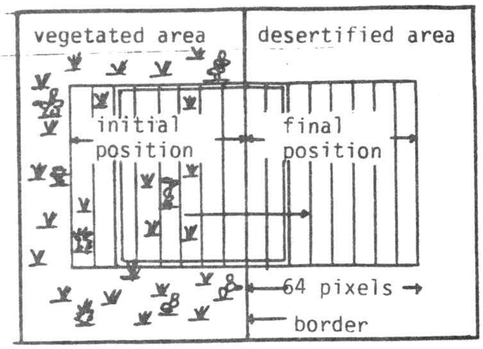

Figure 4. Scheme of the Bulldozer experiment which shows the displacement of the window each 8 pixels for a total of 9 positions.

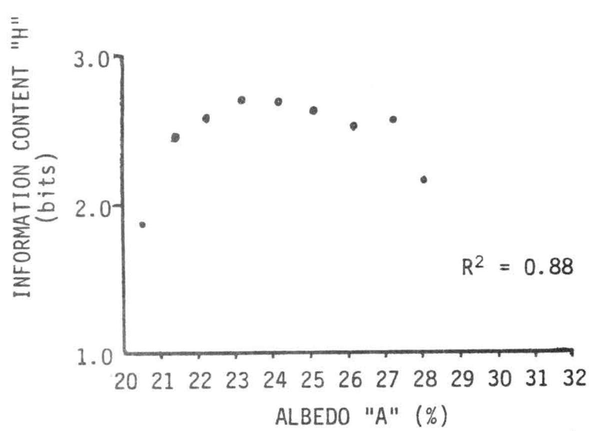

Figure 5. Results from the Bulldozer experiment using data from 1979.

The ALBEXP.32 Experiment. This experiment was designed to observe in a more direct way the assumptions of the suggested model of desertification. A random selection of 32 (64 x 64 pixel) cells within the test site was made, and the associated mean values of albedo (A) and information content (H) were calculated. It was expected that these values would tend to be aligned along the curve of the general model according to their different degrees of desertification. Assuming ergodicity, even though the cells are different, they should tend to be present near the general curve.

The results obtained made it evident that the supposition of the Bulldozer experiment represented only one special case of reality. It was clear that although all 32 cells were located in similar geographic areas, the evolution of the desertification process was different for each cell. No trend toward the suggested model was found.

The Multitemporal Analysis Experiment. The southest quadrant of the test site (sector D) was subjected to a multitemporal analysis. The data sets for 1973, 1981 and 1982 were registered to the base image of 1979, with an indicated RMS≤50 m. The values of H and A were calculated for each of the 64 cells comprising the sector for each temporal data set. The results of plotting the 4 temporal data sets in the H-A reference plane are showns in Figure 6.

The trajectories of some of the cells are shown in the figure. Some would seem to indicate that the simple measure of albedo (A) would be sufficient (cells D16 and D63) inasmuch as a lowering of the albedo value corresponds to a lowering of entropy. Nevertheless, the cells D23 and D32 indicate opposing tendencies in 1973 and 1979. The same situation is present in cells D67 and D88 in 1973 and 1979. It appears that measurement of entropy, which is dependent on the spatial structure within the cell, can be of value in the measurement of desertification, in addition to the measurement of albedo, which could be more climate dependent.

Figure 7 is a photomap of the 64 cells comprising sector D of the study area, with the suggested information categories superimposed. This is an example of one type of output that could be derived from an information system to monitor the state and advance of desertification.

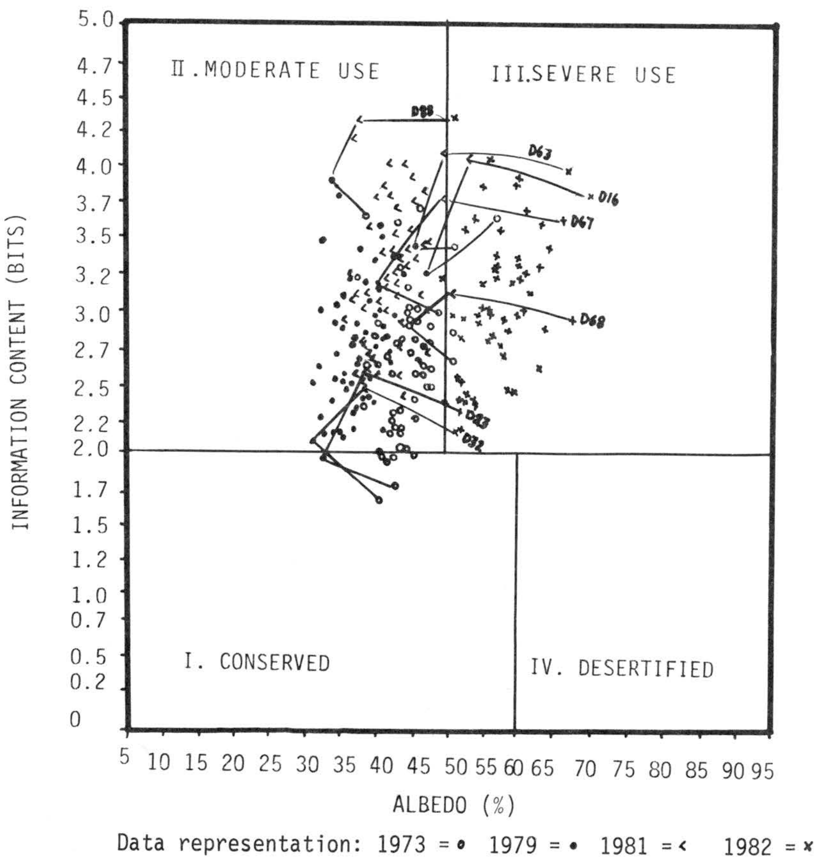

Figure 6. Scattergram showing the relative position of the four sets of data, within the regions or classes of desertification as defined in the model.

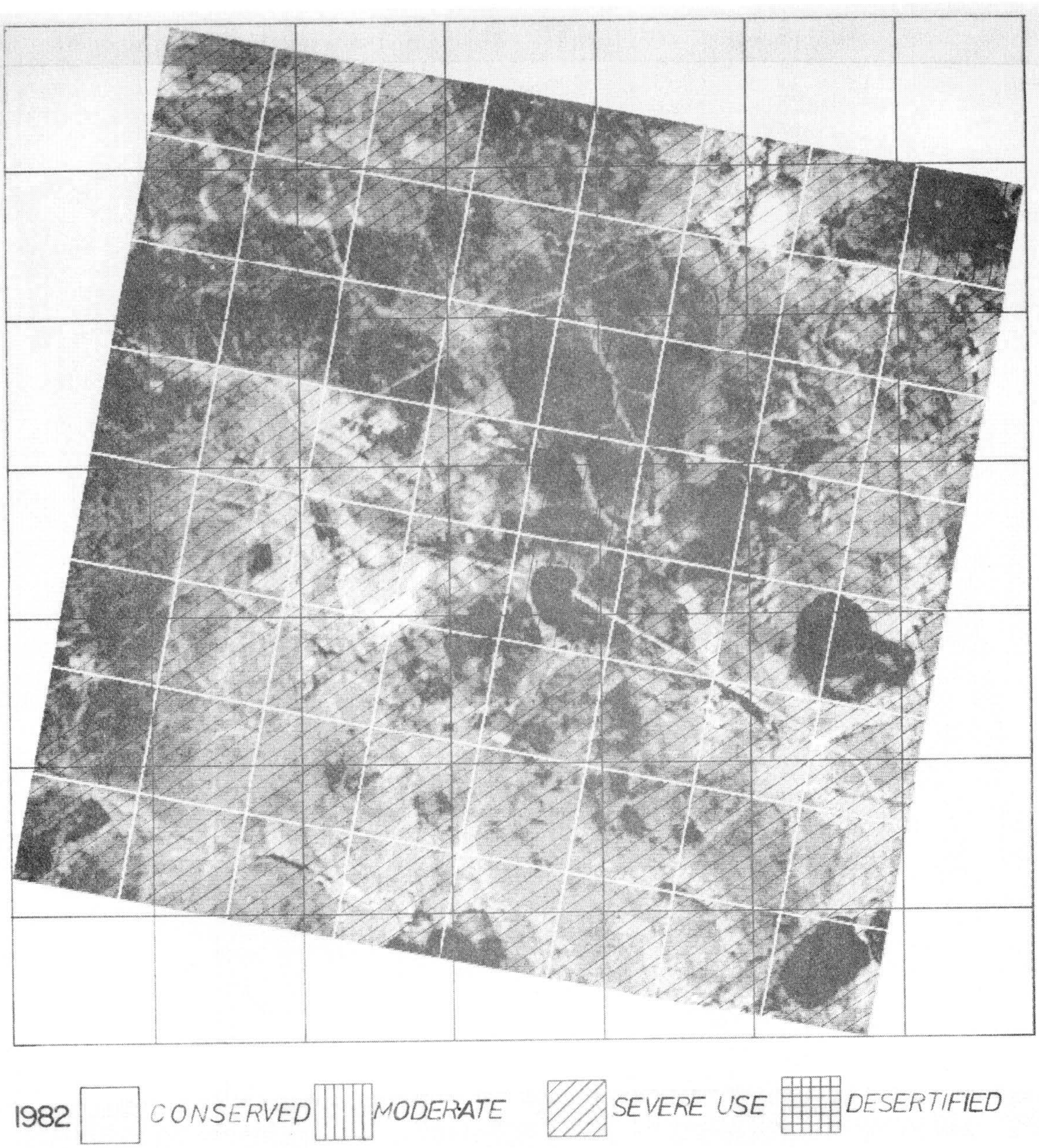

Figure 7. Map of the state of desertification in 1982. Scale of the original map: 1:100,000 The white grid shows the 64 cells from sector D. The black grid shows the reference metric coordinates (UTM) each 5 Km.

VII. DISCUSSION

The boundaries of the information categories of reference system shown in Figure 6 were arbitrarily established. Further studies should develop more objective criteria for determining these boundaries.

The use of systems methodology has permitted a more quantitative denotation to the concept of desertification, and in addition to the more usual concept of biological productivity, we have introduced the concept of order. In this manner, two distinct conditions of desertification can result for the same condition of biological productivity.

It was observed during the bulldozer

experiment that the indicator proposed by Coiner (1980) of the correlation "r" of Landsat bands 2 and 4 is not linearly related to the progressive devastation of the vegetation. However, it is believed that his other two indicators (covariance of bands 2 and 4, and percentage of variation explained by the first eigenvalue of the multispectral space) are probably more adequate than the entropy as measures of the mean information content of a cell. In the bulldozer experiment we found both to be significantly related in parabolic form to the gradient of albedo in each simulation. A possible explanation is that the calculation of H requires subjective definition of classes whereas the two indicators of Coiner are defined by the data set in itself.

The use of filters or spatial operators should be studied in more depth to determine the optimum size of the cells.

VIII. CONCLUSIONS

Information content is a state variable of significant value in estimating the state or process of desertification. In this respect, the use of the first eigenvalue and the covariance of Landsat bands 2 and 4 probably will result in two more consistent estimators than the calculation of entropy. More tests are required to confirm this conclusion.

All of our experiments confirmed the value of the use of albedo as an important indicator of desertification. The albedo and vegetative cover are related in inverse proportion, although both seem more influenced by rainfall than measures of information content.

The indicators of desertification commonly used in field visits are at levels of resolution inaccessible to Landsat. Little to no correlation was found between detailed data gathered in the field and Landsat spectral measurements.

Vegetation indices developed for use with Landsat data gave no satisfactory results when applied to the semi-arid test site. Our results suggest that albedo is a better indicator of vegetative cover.

Landsat data can be used to measure the state and process of desertification. However, before implementing the methodology described, it is necessary to resolve the problem of normalization of data and to determine the best measure of information content.

IX. REFERENCES

Anaya-Garduño M. (1983). "Strategies for the prevention of and fight against desertification". In:(Campos-López E.& Anderson, R.J. Eds.). "Natural Resources and Development in Arid Regions" Westview Press, Inc., Boulder, Col.USA.

Coiner, J.C. (1980). "Using Landsat to monitor changes in vegetation cover induced by desertification processes". Proceedings of the 14th Int. Symp. on Remote Sensing of Envir.; ERIM, Ann Arbor, Mich. pp. 1341-1350.

Dalsted, K.J. and Myers, V.I. (1983). "Remote Sensing to detect desertification processes", In: (Campos-López E. & Anderson, R.J. Eds.)."Natural Resources and Development in Arid Regions", Westview Press, Inc., Boulder, Col.USA.

DeCarvalho, V.C., Lombardo, M.A. (1980). "Preliminary analysis of the potential of Landsat imagery to study desertification". 14th Int. Symp. on Remote Sensing of Environment; April, 1980, San José, Costa Rica; ERIM, Ann Arbor, Mich., Proceedings.

De la Torre, J.C. (1984). "Un Modelo del Proceso de Desertificación en un ecosistema Semiárido mediante Datos Digitales Multiespectrales Landsat". Tesis de Maestría; UIA, México.

ERL/NASA (1980). "Earth Resources Laboratory Applications Software. A Geobased Information System". Report No. 183.

Frank, T. (1984). "Assessing change in the surficial character of a semiarid environment with Landsat Residual Images". Photogrammetric Eng. and Remote Sensing, Vol.50. No.4, pp.471-480.

García Castañeda, F. (1978). "El marco fisiográfico de la desertificación en México". In: (Medellín F. Ed.) "La Desertificación en México". Cap.3. UASLP, México.

Graetz, R.D. and Gentle, M.R. (1982). "The relationship between reflectance in the Landsat wavebands and the composition of an australian semiarid shrub rangeland". Photogrammetric Eng. and Remote Sensing, Vol.48. No.11. pp.1721-1730.

Hellden, V. and Stern, M. (1980). "Evaluation of Landsat imagery and Digital data for monitoring desertification indicators in Tunisia", Proceedings of the 14th Int. Symp. on Remote Sensing of Environment; April, 1980, San José, Costa Rica; ERIM, Ann Arbor, Mich. Vol. III, 1601-1610.

Hellden, V., Olson, L. and Stern, M. (1982). "Approaches to desertification monitoring in the Sudan", Proceedings of an EARSel-ESA Symposium, Igls, Austria, 20-21 April; pp.131-144.

Klir, J.G. (1969). "An approach to general systems theory". Van Nostrand Reinhold Publishers, USA.

Mouat, D.A. and Hutchinson, C.F. (1983). "Techniques for vegetation Mapping in semiarid regions"; In: (Campos-López,E. & Anderson, R.J., Eds.) "Natural Resources and Development in Arid Regions" Westview Press, Inc,. Boulder, Col.USA. USA.

Noy-Mier, J. (1973). "Desert Ecosystems: Environment and Producers", Annual Review of Ecology and Systematics. Vol.4; Richard F. Johnston Eeitor, USA.

Otterman, J. (1974). "Baring High-Albedo Soils by Overgrazing: A hypothesized desertification mechanism", Science Vol.186, Nov. 8, 1974.

Otterman, J. (1981). "Satellite and man field studies of Man's impact on the surface in arid regions"; Tellus, 33, pp.68-77.

Robinove, C.J., Chávez, P.S., Ghering, D. and Holmgren, R. (1981). "Arid Land monitoring using Lansat albedo difference images", Remote Sensing of Environment 11:133-156.

Robinove, C.J. (1983). "The logic of Multispectral classification and mapping of land", Remote Sensing of Environment 11:231-244. ERIM; Ann Arbor, Mich. USA.

Robinson, V.B., Coiner, J.C. and Barringer, T.H. (1982). "Dynamic modeling of vegetation change in arid lands", Proceedings of the First Thematic Conference; International Symp. on Remote Sensing of Envir.; Cairo, Egypt; January, 1982.

Rubinstein, M.F. (1975). "Patterns of problem solving", Prentice-Hall, Inc. Englewood Cliffs, New Jersey, USA.

Sutherland, J. (1975). "Systems Analysis, Administration and Architecture", Van Nostrand Reinhold Co. N.Y., USA.

UNCOD/ONU (1977). "United Nations Conference on Desertification, August 19-September 9, 1977. Nairobi, Kenya, Proceedings.

Vemuri, V. (1978). "Modeling of Complex Systems. An introduction". Academic Press, Inc.; N.Y. USA.

Warren, P.L. and Hutchinson, C.F. (1982). "Indicators of rangeland change and their potential for Remote Sensing", Internal Report. Arizona Remote Sensing Center, Office of Arid Lands Studies, University of Arizona, USA.

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