FIVE REASONS WHY GEOGRAPHICAL INFORMATION SYSTEMS ARE NOT BEING USED EFFICIENTLY FOR LAND RESOURCES ASSESSMENT

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ABSTRACT

Current state-of-the-art geographical information systems appear to be ideal tools for all forms of land resources assessment and rural landuse planning. Yet in contrast to land information systems, utility applications and topographic mapping, GIS are not being used for land resources assessment as effectively nor as widely as possible for at least five major reasons. These are:
1. The dynamic but often imprecise, complex and stochastic nature of many natural phenomena is poorly captured and handled by current GIS methods using simple Boolean logic, map overlay and conventional thematic mapping techniques.
2. Many current soil science, ecology and land evaluation methods currently use only single site-specific data.
3. GIS for land resources assessment are too expensive.
4. A shortage of skilled personnel.
5. Remote sensing and image analysis have taken investment away from more direct methods of land resources assessment.

INTRODUCTION

At first sight, current, state-of-the-art geographical information systems are ideal tools for all forms of land resources assessment and rural landuse planning, both in developed and in developing countries. Yet in contrast to land information systems, utility applications and topographic mapping, apart from certain notable exceptions, GIS are not being used for land resources assessment as effectively nor as widely as possible. There are at least five major reasons why this is so. They are:

1. The dynamic but imprecise, complex and stochastic nature of many natural phenomena is poorly captured and handled by current automated methods of classification, Boolean logic, map overlay and conventional modelling and thematic mapping techniques (c.f. Burrough 1986).

2. Many current soil science, ecology and land evaluation methods pay more attention to data located at specific points (monitoring) than to spatial distributions.

3. The limited markets and thus restricted profit motives for appropriate system development are reflected by the high capital costs of many commercial systems.

4. The lack of skilled personnel, particularly in third-world countries, and the technology gap between system designers and potential users.

5. Remote sensing and image analysis have diverted much finance and brain power away from more direct methods of land resources assessment.

1. Describing natural phenomena

Any system of land resources assessment is totally dependent on the quality of the data that are used for making statements about the feasibility or otherwise of various kinds of land use. In most kinds of land resource assessment, quantitative or otherwise, data collection is often carried out separately from data analysis. Various data collection technologies (field surveys, remote sensing, sampling methods) are used to build a database of information that is considered to be relevant and necessary. This database is today often available in digital form on a computer.

It is axiomatic that the database will not serve its purpose unless it enables the user to retrieve and manipulate the data it contains in the ways required for the purpose at hand. For natural resources analysis it is essential that the fundamental concepts used by the field scientist to describe and collect basic units of data are appropriate for the problem at hand and are not dictated by the structure of an information system.

The field scientist usually organizes landscape data in terms of 'phenomenological' units - mountains, terraces, solifluction layers, soil series, textural horizons, catchment areas, geotopes and so on, that he has attempted to recognize as physical entities that can be uniquely described. These phenomenological units are then very often meticuously described in terms of their non-spatial attributes, which are organized in classes, and their spatial extents, which are represented by polygon boundaries on thematic maps. The net result is a database in which the fundamental units or building blocks are stylised abstractions of reality (Figure 1). Note that these units imply a static, or unchanging landscape; dynamic landscape change must be treated separately.

If natural landscapes could always be fully described by the data model given in Figure 1, we would have few problems. The basic units of natural landscapes would then be very similar in structure to the well defined and well delimited parcels and land units that can be managed so well in current land information systems. Unfortunately, reality is often otherwise. There are three aspects that should be considered, namely the nature of the spatial boundaries, the problem of internal variation, and the problem of dynamic change.

Boundaries. In practice a cartographic boundary may describe a) an abrupt change in the value of a phenomenon, b) intervals along a trend or c) a chance occurrence resulting from adjacent observations just happening to fall on opposite sides of an a priori class boundary (Figure 2). Clearly, whether a boundary is type a), b) or c) will have severe implications for the outcome of analyses using map overlay techniques in GIS.

Also, most boundaries on thematic maps of natural resources such as soil or vegetation have been interpreted either from field observations, or indirectly from aerial photographs or remotely sensed images. Because of the complex nature of landscapes, and the variation in the skills of the surveyors, the resulting interpreted boundaries can be drawn in many ways (c.f. Bie and Beckett 1973). Note that the average density of boundaries on soil maps, for example, seems to owe more to the scale of the paper map on which the survey was compiled, than to inherent differences in terrain (Burrough 1983, 1986).

Spatial variation within boundaries. The thematic map model assumes 'homogeneity' within boundaries. For some phenomena, in some landscapes, this may be a reasonable approximation of the truth, but in other situations it is clear that there is considerable spatial variation within the mapped units. In recent years there have been major advances in ways of describing spatial variation (e.g. Nielsen and Bouma 1985, Webster 1985), but these methods have not yet been incorporated into most commercially available geographical information systems. It is only with respect to methods for modelling landform, using digital elevation models, that commercial systems have provided exciting and powerful new tools for handling continuous variation in spatial data.

Conceptual units and Boolean logic. Most information systems currently available use sharply-defined conceptual classes or spatial units as basic entities. These entities are at the heart of relational databases which use of Boolean logic for data manipulation and retrieval. Many 'expert systems' having strict rule-based logic use the same basis of well defined data entities and the same is true of current qualitative land evaluation methods (e.g. McRae and Burnham 1981). "Pattern invoked programs" (Negoita 1985) are activated whenever certain conditions hold:

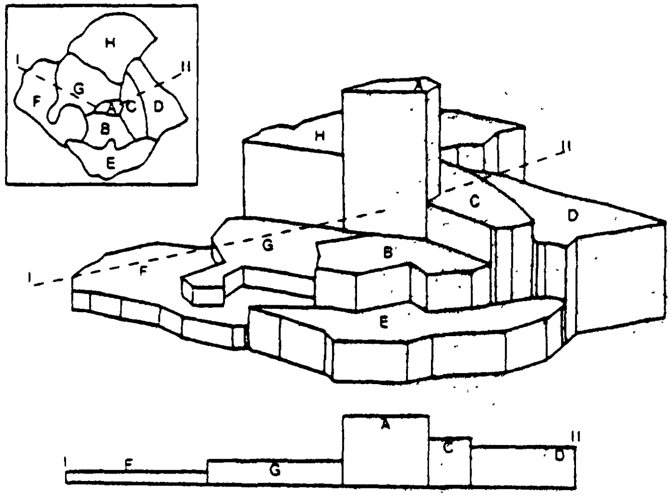


Figure 1. Many thematic maps of natural resources imply discrete, stepped distributions enclosing homogeneous areas.

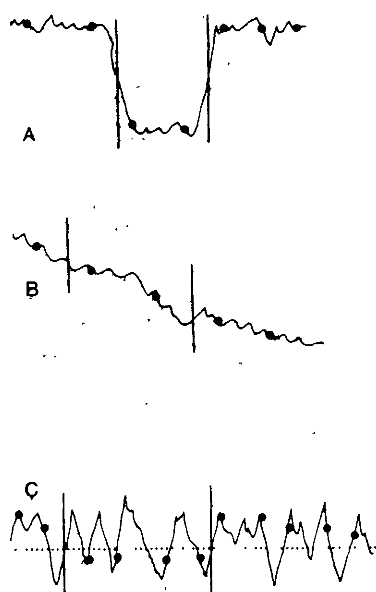


Figure 2. Three variants on soil boundary location from point observations.
A. abrupt change,
B. splitting a trend,
C. Sampling variation - observations happen to sample points falling on opposite sides of a classification boundary.
• sample sites.
'True' variation.

Condition IMPLIES action

This is usually coded by IF ...... THEN statements: For example, IF soil is non-alkaline AND slope < 5% THEN site is suitable for irrigation. Many systems of land evaluation, including the FAO 'framework' (FAO 1976), are based on this kind of logical equivalence.

Although these conventional methods of reasoning have brought us a long way, studies of the spatial and multivariate variation of soil and other natural resources are demonstrating that the simple concept of discrete, basic, homogenous units is inadequate for further progress in quantitative land resource assessment. We cannot be completely certain that all statements made about the data units are 'true'in the sense of being exact and precise. We know that it is impossible to determine the value of soil, water or other properties exactly - Table 1 - (c.f. Beckett and Webster 1971, Pleijsier 1986), we know that spatial variation of soil occurs within map units (c.f. Nielsen and Bouma 1985), and we know that map unit boundaries may reflect anything from abrupt changes in soil through attempts to divide a trend, to chance effects caused by noise.

Table 1. Variation in the estimated values of soil properties when the same samples were analysed by a number of well-known international laboratories using the same methods.#

Soil Property*	Number of labs.	Minimum	Maximum	Mean	Standard deviation
Clay % (11)	37	9	60	39.84	9.67
Clay % (19)	37	19	36	26.16	3.88
pH-KCl (11)	43	5.8	7.5	7.11	0.31@
pH-KCl (19)	43	4.3	6.0	5.24	0.26@
Exch K (11)	38	0.04	0.77	0.32	0.15·
Exch K (19)	39	0.26	4.55	2.00	0.73·

Data from Pleijsier (1986).
* Numbers in parentheses give the sample identification numbers: 11 is from the B horizon of a saline/calcareous/gypsiferous soil from Syria, 19 is from the A horizon of a typic argiustoll from the USA. @ means and standard deviations for pH are for measured values, and not via transformation to H+ concentrations. · Means and standard deviations for Exch K calculated ignoring single extreme values of 2.00 and 16.66 meq./100g oven dry soil, respectively.

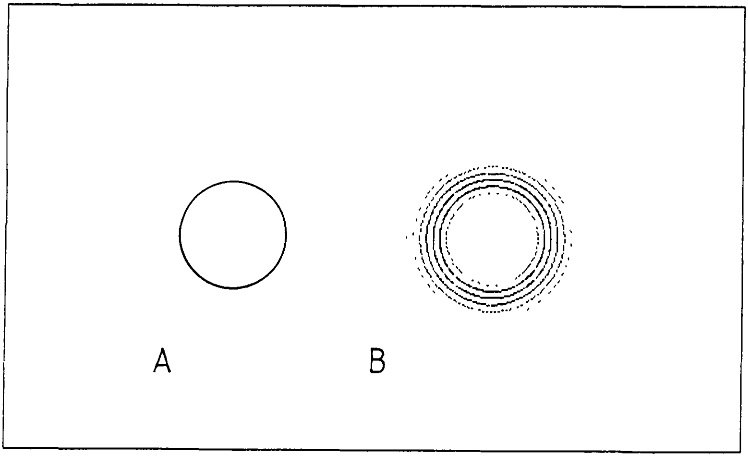
So, we conclude that the basic units of information in natural resource data are not always well defined, but may be diffuse or 'fuzzy' (Figure 3.). For many years field scientists have been using imprecise terms such as 'moderately well drained' or ' few mottles' or 'steep' to express their findings, yet they have been forced by the conventions of logical data analysis to define them in terms of strict intervals. Modern information theory, linked to geographical information, can provide an answer.

Fuzzy logic When working with quantitative variables, we can use discriminant analysis or maximum likelihood methods to establish the degree of statistical probability that any individual soil observation belongs to any given class (e.g. Webster and Burrough 1974). When working with logical statements, we can use the concept of possibility or of a 'certainty factor' (CF, CF $-1 < 0 < +1$) which indicates the certainty with which each rule is believed (Negoita 1985, Zadeh 1965). Inexact reasoning is based on the construct:

IF A (to degree x) THEN B (to degree y)

Such constructs can be applied to decisions involving phenomenological data and situations in which there might be more than one correct decision. As Figure 4 shows, the intersection of two fuzzy subsets (be they spatial or conceptual) will yield very different results depending on the levels of the certainty factors that are chosen. The answer obtained from intersecting two sets no longer has to be 'yes' or 'no', it could also be 'maybe'. In 'eyeball' studies of land evalution, the levels of the certainty factors are determined intuitively by experience; skilled 'experts' will make better choices than novices. Because our current methods of data collection and data structures do everything possible to avoid the real problems of the inherent fuzziness of landscape and spatial variability, methods of natural resource evaluation that use discrete units and strict rule-based logic cannot perform as well as we would like.

Propagation of errors in GIS. Many commercially available systems allow the user to set up cartographic models, which are essentially flow charts governing the transformation or selection of basic data in order to draw conclusions. Because of the limited facilities for recording information about within-unit variability (even if the information was available, which it often is not), these models pay no attention to the propagation of errors. Consequently, only one result (usually in the form of a beautiful graphic product) comes out of the computer; there is no information about possible margins of error.



A. USUAL BOOLEAN SET B. FUZZY SUBSET

Figure 3. Comparison of a normal Boolean set with a fuzzy subset.

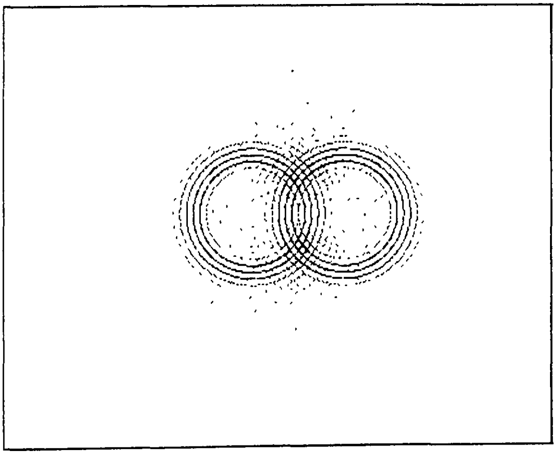


Figure 4. The intersection of fuzzy subsets.

Statistical methods of analysing error propagation have been available for many years (Parratt 1961, Burrough 1986) but so far have found little application in standard GIS methodology. Few users seem to realise the implications of error propagation, however, believing that the quality of the results of a GIS analysis are determined by the cartographic quality of the end product. For example, if an empirical GIS model requires six terms, each having a relative error of 10%, to be multiplied together, the result will have a relative error of 24%. Few natural resource data can be determined with an accuracy of ±10% at a price resource survey agencies can afford.

2. Site-specific studies

Because of the complexity of many natural resource phenomena, there has always been a tendency to study them intensively at a few, 'representative' sites, from which conclusions are drawn and extrapolated over large areas. Examples are the study of soil erosion along specific transects, the monitoring of environmental quality or the modelling of crop production at given locations. There is a great challenge now to find new ways in which detailed, local studies can be applied to whole landscapes. Because of the limitations imposed by the basic 'building block' approach outlined above, in which 'second-hand' resource data are used for extrapolation, it seems sensible to approach the problem by integrating the data collection and data analysis phases into a single system. Such a system would also have to include dynamic models of the movement and spatial variation of air, water and pollutants in order to allow proper extrapolation in time and space. It is a challenge to the natural resources disciplines to develop the necessary strategies that can be used effectively here so that the new methods can be incorporated in the next generation of GIS.

3. System costs

Geographical information systems are expensive tools. The high costs of hardware, good software and skilled personnel have restricted the widespread use of GIS and also have restricted critical assessment of their worth. Manufacturers have very naturally been prepared to invest in areas where there has been a chance of good returns, and it has been attractive for them to use the same technology and software for land information systems (i.e. well-defined parcels with simple attributes and high quality graphics) as for natural resources. It is only recently, with the arrival of small, cheap but powerful processors, and good raster display systems, that more people can work with natural resource data in ways that have not been dictated by CAD/CAM system design.

4. Training

The high costs of systems linked to the rapid changes in technology have meant that until recently, only students of natural resources in the richest countries of the world have be able to receive training in GIS. Because until recently, few received training, the acceptance of GIS, and understanding of their potential have been retarded. As more people become aware of the potentials, it is to be expected that within the natural resource disciplines there will be trends away from the original qualitative approach of classification into static spatial and conceptual units towards more emphasis on quantitative, dynamic understanding of complex natural processes.

5. Remote sensing

Remote sensing and image analysis are natural parts of any geographical information systems used for natural resource assessment, yet in the past, they have often functioned as independent disciplines having little in common with the field sciences. Their technical nature has attracted many able scientists who have found the intellectual challenges of computer science more stimulating than those provided by field work. Many government agencies, particularly the military, have invested much larger sums in remote sensing than in basic research in natural resources, yet fundamental understanding of the patterns of distribution and the processes at work in natural resources is absolutely essential for the proper use of remote sensing as a tool in resource analysis. Rather than continue to invest large sums and skilled persons in further refinements in image classification and analysis, let us attack some of the fundamental theoretical and practical problems of describing and modelling the complex, dynamic aspects of our natural resources base upon which all life depends.

REFERENCES

Beckett, P.H.T. and Webster, R. 1971. Soil variability - a review. Soils Fert. 34: 1-15.

Bie, S.W. and Beckett, P.H.T. 1973 Comparison of four independent soil surveys by air-photo interpretation , Paphos area (Cyprus). Photogrammetria 29:189-202.

Burrough, P.A. 1983. Multiscale sources of spatial variation in soil. I. J. Soil Science. 34: 577-597.

Burrough, P.A. (1986) Principles of geographical information systems for land resources assessment. Oxford University Press.

Burrough, P.A. and Webster, R. (1976) Improving a reconnaissance classification by multivariate methods. J.Soil Science 27: 554-71.

McRae, S.G. and Burnham, C.P. (1981) Land Evaluation. Oxford University Press.

Negoita, C.V. (1985) Expert systems and fuzzy systems. Benjamin/Cummings, Menlo Park, California.

Nielsen, D.R. and Bouma, J. (1985) Spatial analysis of soil data. PUDOC, Wageningen.

Parratt, L.G.(1961) Probability and experimental errors. Wiley, New York.

Pleijsier, L.K. (1986) The laboratory methods and data exchange programme. Interim report on the Exchange Round 85-2. International Soil Reference and Information Centre, Wageningen.

Webster, R. (1985) Quantitative Spatial Analysis of Soil in the field. Advances in Soil Science Volume 3, Springer-Verlag New York.

Webster, R. and Burrough, P. A. 1974. Multiple discriminant analysis in soil survey. J. Soil Science. 25: 120-134.

Zadeh, L.A., (1965) Fuzzy sets. Information and control, 8:338-353.