SPATIAL TOOLS FOR LAYMEN, NATURAL RESOURCES MANAGEMENT BY EXPERTS

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ABSTRACT

In the management of natural resources increasing emphasis is placed on relationships over time and space, between species and the human impact overall. The manager of these resources needs to incorporate ever more data in the decision-making process and applies geographic information systems (GIS) for the management and analysis of spatial data. Most GIS, however, are ill equipped to handle the fuzzy, noisy data of the natural environment and their algorithms perform poorly on equally poorly represented data. This paper gives an overview of the characteristics of spatial data describing the natural environment and the limitations of current GIS in representing this. Four key points are addressed that, once implemented using the glue called metadata, would enable a GIS to better respond to the needs of the domain expert in natural resources management.

1 INTRODUCTION

The sustainable management of Earth's natural resources has been the focus of many international gatherings, of which the United Nations Conference on Environment and Development (Earth Summit) in Rio de Janeiro, 1992, is perhaps the most widely known. The Rio Declaration and recommendations made at the Earth Summit form the basis of many subsequent international treaties and national policies for sustainable development. The Earth Summit clearly indicated the lack of appropriate options for the sustainable management of land, hydrology and forest, combined with a lack of reliable and consistent data (UNCED, 1993). Since the Earth Summit, impressive advances have been made in several fields of science related to sustainable development. Simultaneous technological advances have provided the raw data and framework necessary to apply the newly acquired knowledge to actual cases.

When it comes to the operational management of natural resources, however, the advances made at universities and in research institutes are as yet of limited applicability to planners and managers of field offices. This is particularly true for developing countries, with their limited financial and human resources and often inadequate organizational structures, but it applies also to field offices of resource management agencies in the developed world (Prévost and Gilruth, 1997; Westinga *et al.*, 1999; Hall *et al.*, 2000). The scientific advances are focused on the better understanding of global and regional processes (global warming, climate change, land cover change, *et cetera*), while the development of appropriate methods and tools for local management is given much less attention. A better understanding of the major processes affecting the natural resource base, and potentially threatening the human society, is indispensable for defining a framework for sustainable development, but unless adequate management systems are developed to implement such a framework at the local level, the understanding will not help in averting degradation of natural resources.

Over the last decades the state of the world's natural environments has become a serious concern for many people. The ecological and aesthetic degradation of the landscape in the industrial economies, rampant deforestation in the tropics and desertification in Africa and North America are the highly visual and widely publicized examples of what was predicted already 30 years ago by the Club of Rome. As a result many non-governmental organizations (NGO) have sprung up to take direct action, locally, nationally and globally. Governments have enacted environmental protection laws and international protocols have been drafted to protect the natural environment from the predatory effects of the neoclassical economy. For the manager in the field office this meant seeing the forest not as a collection of trees, but as an ecosystem. Similar changing views confronted the managers of other resources and they need data, and more data, to translate these views into practice.

In recent years the availability of imagery from earth observing systems (e.g. Landsat TM, Spot, IRS) has substantially increased and become more accessible, and yet another significant increase in both volume and quality is expected in the next few years (Glackin, 1998). This, combined with the new approach to integrated land resources management developed by the research community, is both solving and compounding the difficulties faced in the operational management of natural resources. The better and cheaper data make use of satellite imagery a viable option for many management purposes. The analysis and application of spatial data, however, require expert knowledge and experience, something that is all too often lacking at the level where operational decisions are taken and implemented (Van Laake, 1999). As a result, analysis of spatial data is often inadequate, or even inappropriate, yielding generalized notions of the physical environment with no indication of correctness or significance, and management is based on interpretation on the basis of experience. This is probably less of a problem in the industrialized nations at higher geographical latitudes, with their abundance of highly skilled personnel and relatively "simple" natural resource conditions. In the tropical countries, however, the highly dynamic ecological processes need to be analyzed and managed by scarce institutional and human resources.

This paper outlines the use of spatial data in natural resources management (NRM) and some of the fundamental problems that need to be dealt with before an efficient use can be made of it (section 2). We will continue to propose a framework to address these problems (section 3), such that the spatial layman can revert to being a domain expert in the management of natural resources.

2 SPATIAL DATA AND TOOLS IN PRACTICE

2.1 Spatial Data for Natural Resources Management

In the management of natural resources a surprisingly small number of basic data sets is generally being used, with additional data sets being used for specific applications (see for example IMSD, 1996; Westinga *et al.*, 1999; Van Laake, 1999). Topography, usually in the form of a Digital Elevation Model (DEM), is almost universally used, as are surface-derived data (slope, aspect and hydrology), soils, land cover and anthropogenic features (roads, urban areas, utility lines, etc.).

With the advent of Geographic Information Systems (GIS) the users of spatial data acquired a tool for data management and manipulation. Up to only a few years ago the bulk of data being input into GIS consisted of digitized paper maps. Through this digitization error was added to the database, but the manipulation and analysis of the data can be considered free of computational error, although the computations might introduce error through conceptual limitations. One striking conceptual limitation of current commercial GIS is the absence of the fourth dimension, time. This limits GIS to the representation of state, and only the most astute user may be able to deduct change through the comparison of subsequent states. This is a far cry from modeling spatial processes (i.e. infer change from a state through some parametric process that itself may be dependent on the state) that would better suit the decision-making process in NRM.

GIS, however, was developed primarily for urban applications, since it was here that the software companies found the resources needed for development. As a result, GIS carry some important assumptions that are valid for the urban environment (e.g. relatively static, well-defined spatial features, exhaustive-exclusive use of space) but not necessarily for the description of natural features. These assumptions force the representation of these natural features into a model that limit their fidelity and applicability.

2.1.1 The Nature of Nature. Outside of the urban world, where cadastral maps do not reach and utilities limit themselves to air traffic lanes, things are fuzzy, dynamic, uncertain. Spatial features – a forest, a winding river, a soil characteristic – do not behave very well. They change gradually, over long distances or short distances, or both. They change over time. They change seasonally, or unpredictably. They interact with each other, and often we don't know how or when or where.

GIS, with their roots in that urban world of cadastral surveyors, are not very well adapted to this confusion. The data model does not fit the chaotic reality of Nature, and the analytical procedures perform poorly. Their deterministic properties are just not right for uncertainty, probability and fuzziness (Burrough and Frank, 1985; Lagacherie *et al.*, 1996; Burrough and McDonnell, 1998). Satellite imagery does have a large potential for NRM, in that it provides synoptic, repetitive coverage of the land and land cover. However, the quality of the data that is generally available today limits its use to meso and macro scale processes (e.g. generalized field or plot, to descriptive landscape, to detailed regional and global studies), while actual management of the local resource often requires much more detailed information (Holmgren and Thuresson, 1998; Van Laake, 1999).

2.1.2 Error and Uncertainty. Any kind of (spatial) data, for urban applications as well as for NRM, has some uncertainty and error associated with it. These errors can be conceptual – do we understand what we are observing and describing or analyzing? – or related to the way we abstract the perceived reality into a model and analyze it. Uncertainty is present in everything we observe and measure. Even formal sampling strategies observing the Nyquist theorem provide little more than reduced uncertainty, that is, reduction to manageable limits. The onus in data management for NRM is not to eliminate error and uncertainty, but to learn to live with it. This is of course nothing different from the way that Mankind managed its affairs for more than 99% of its existence on Earth, but now at least we have some means of assessing its magnitude and impact.

2.2 Tools for Spatial Data Handling and Analysis

The average user of a GIS in NRM is a layman in data management and spatial analysis. Using today's commercial technology the domain expert has to convert into a GIS expert in order to operate a GIS (Burrough, 1992). But is that not too much to ask? Thus NRM would be driven by what the technology has to offer, rather than concentrate on the challenges posed by the resource itself and the changing view of what managing this implies. Such a requirement is really only demonstrating major weaknesses in current GIS: the inability to abstract spatial operations to a general application-specific framework, and the failure to envelop low-level spatial procedures into high-level operations. As an example: most GIS support a wide variety of geographic projections, and very likely including projections that are equi-distant or azimuthal; however, no system on the market today will alert the user on the feasibility or error when he or she requests an area to be calculated from data in this projection. Trivial as this may seem, it is indicative of the kind of domain and product-specific knowledge that the user is supposed to possess.

The tools used to perform spatial analysis have generally been developed with specific circumstances in mind, using assumptions and generalizations valid for those specific circumstances. Unfortunately for NRM, most of these assumptions and generalizations do not hold for representing the natural world.

2.2.1 Spatial Operations in Natural Resources Management. In NRM one is usually working with multiple layers simultaneously. For example, in land evaluation multiple layers of spatially explicit data are evaluated and combined to produce a new spatial layer that carries information from the original layers to identify suitability of areas for particular land uses.

Class changes in thematic layers are usually gradual, although they may not be represented as such. In soil classification and mapping, for instance, elaborate schema have been developed to categorize multiple, gradually changing parameters into a limited number of exhaustive and exclusive classes. Being developed for thematic mapping, this neatly fits the data representation in current GIS, but every soil scientist will attest to the arbitrary nature of some of the classifications and the difficulty of classifying certain combinations of parameters. When this soil map is used in subsequent analyses the original, smooth change in parameters is replaced by a discrete interval, and information is lost.

Overlaying discrete, thematic maps produces spurious polygons that may be caused by imperfections in the (representation of the) data, or they may be geometrically valid but logically insignificant (Veregin, 1989; Wang and Hall, 1996). Such polygons are traditionally removed using deterministic approaches based on areal extent and adjacency, without taking explicit knowledge of what the polygon represents into consideration. The probabilistic, fuzzy characteristics of spatial data from the natural world do not lend themselves well to such simplistic procedures and the explicit inclusion of fuzziness in spatial data actually invalidates the standard procedures (Hootsmans, 1996).

2.2.2 Managing Error and Uncertainty. Most current GIS are unable to handle error and uncertainty. Errors in representation (e.g. the failure to accommodate uncertainty in data, generalizations) and processing are obvious, yet not fully understood (Goodchild, 1992; Wang and Hall, 1996; Molenaar, 1997). While there are methods to assess error in spatial data quantitatively these usually limit themselves to global quantities. For example, the confusion matrix used in the assessment of the classification accuracy of remotely sensed imagery gives an indication of the fidelity of the classification throughout the image; there is no explicit spatial information contained in the error estimate.

The errors are compounded when multiple sources of spatial data are combined, as is often the case in NRM. There are the errors contributed by the source data sets, and there is the error that originates from the processing algorithm. Most of the algorithms in current GIS carry assumptions about the nature of the problem and the data it operates on (Openshaw and Openshaw, 1997; Burrough and McDonnell, 1998). In NRM, these assumptions often do not hold, as was stated earlier in this paper. There are no adequate methods available today to assess the effect of these assumptions on the processing, other than confronting the results with independent data. In fact, most GIS do not incorporate any means to record and control error, leaving it up to the user to assess the quality of the output. The spatial layman is obviously not well equipped to undertake such a task.

2.2.3 Metadata. Metadata standards have been developed to describe spatial data sets for the purpose of finding data sets fit for a particular purpose, either within the own organization or externally. The emphasis has been more on *finding* data externally, than on managing local data or assessing *fitness* of the data. For example, the United States Federal Geographic Data Committee's Content Standard for Digital Geospatial Metadata does not mandate the use of data quality information, which is described as "a general assessment of the quality of the data set" (FGDC, 1998). And indeed, the indicators that are prescribed parts of the data quality information section are quantitative and global, or qualitative. Lineage and processing steps are merely descriptive, and do not allow for thorough analysis (Clarke and Clark, 1995).

A more practical shortcoming of current metadata systems is the fact that they are designed to describe the spatial database, leaving the interpretation of the metadata to the user of the data set. This is adequate for data at the highest level of abstraction (e.g. contact information, location, format, distribution), but tedious, to say the least, for the data describing the entities contained in the data set.

2.3 Domain Experts, Laymen in Spatial Data Handling and Analysis

Typically, the operator of a GIS has a bachelor's degree in a specific field and general knowledge of computer applications. Many organizations lack the resources or the scale of operations to employ experts in the use of spatial data. This is, of course, the ideal configuration; the objective is to manage the resource and not the spatial data, after all. However, the tools for data manipulation and analysis for NRM are far from ideal and require training and experience before any sensible use can be made of the tools.

Davies and Medyckyj-Scott (1994) conclude that "many current GIS are not ideally suited for the new, non-specialist or casual user". The reply from the developers of the tools has been to provide training in the use of the specific product (a practice that is still very common) and the development of applications more geared at specific functionality (e.g. customization of a generic GIS to support forest management). The first reply forces the domain expert to become a spatial layman, while the second does nothing to remove the fundamental shortcomings of current GIS outlined above. In fact, the applications for NRM are few and focus on the more deterministic uses of the natural environment, such as timber management, geological exploration and watershed management for a singular purpose (e.g. hydropower).

The domain expert is a decision-maker and needs a tool to manage and analyze the bulk of (spatial) data required to make those decisions. The deterministic, spatially exhaustive and exclusive data model of current GIS, the absence of error assessment and management, the inability to model dynamic processes and the requirement to keep track of data and operations invalidate the use of current GIS for NRM. But in the absence of viable alternatives GIS is being used extensively, and usually with disregard of its limitations. The next section of this paper will present a number of issues that could potentially remediate some of the weaknesses in current GIS.

3 MAKING SPATIAL TOOLS MORE INTELLIGENT

To be truly useful in NRM, GIS has to evolve from a data-centric tool to a process-oriented toolbox, with extensive functionality related to data management. With the changes elaborated above (improved knowledge about natural processes, changing perception of the natural environment, integrated policies and regulations regarding use of the resources, public involvement, explosion in data availability and quality) come new requirements to the manager and new requirements to the GIS. Below are the key issues that relate to these requirements:

- **Managing the database** To find data being used for a small office or project, stored on a local machine, is usually relatively straightforward. But with the explosion in available data, and the general trend in data storage and retrieval (i.e. LANs, internet), the user will be increasingly groping in the dark. Where is my data? What is in this data set? Responding to requests for information or data sets from external parties (other organizations, the public) can become cumbersome and require extensive effort.

- **Mining the database** Managing the spatial database is only one aspect of dealing with a large quantity of data. More important still: how do we get relevant information out of the mass of data. The current developments are both enabling the natural resources management through the availability of more and better data, but simultaneously it is invalidating the old ways of analyzing it. The sheer size of the database may still be tackled by throwing more sophisticated hardware at it, but what about its content? New data products have a higher information content than older products, both in terms of what can be identified and of what can be analyzed or modeled.

- **Uncertainty, Error and Error Management** The world of NRM is probabilistic and fuzzy, both in terms of the spatial organization and extent of features and the processes that govern it. The discrete data models of current GIS are ill equipped to handle such data and the algorithms and visualization tools are not adequate. There are methods to assess uncertainty and error in spatial data, particularly in single layers (e.g. geostatistical procedures, satellite imagery geometric correction and classification), but they are usually limited in applicability or scope and not well suited to the compounding of error through overlays (but see Heuvelink and Burrough, 1993; Woodcock and Gopal, 2000). The absence of a comprehensive suite of error assessment algorithms leaves much of the assessment up to the user. The visualization of uncertainty and error is therefore critical (Hootsmans, 1996).

- **Knowing the Universe of Discourse** The algorithms and the data they operate on should be compatible, and match the criteria established by the user. This means that the algorithms have to be either specific to the data that the user is working with, or that they have very few assumptions about the data at all. The first option more or less mandates the development of algorithms or even entire systems to suit the needs of particular users, a prospect that is not too appealing or appropriate, given the increasing connectivity of people and data. The second option actually has some very interesting aspects that better match the probabilistic nature of data in NRM. Having few or even no assumptions about the data implies the use of generic algorithms performing generic operations. As we have seen, the operations in NRM are generic indeed, mostly selection of features based on simple criteria and combinations of these into new features, but on fuzzy, noisy data. From the field of Artificial Intelligence (AI) a number of procedures can be readily applied to NRM. The probabilistic nature of these procedures perfectly matches the reality of the natural world. Neural nets (e.g. self-organizing maps by Kohonen (1995)), genetic algorithms and cellular automata have already been successfully applied in spatial analysis (see for instance Openshaw and Openshaw, 1997; Burrough and McDonnell, 1998; Woodcock and Gopal, 2000). But despite the potential of these procedures to find order and relationships in the mass of data, it does little to explain what the order and the relationships represent. The power of searching and finding has to be matched by an equally powerful method of explaining, understanding and relating to what is already known.

Managing natural resources with the help of spatial data is almost as complex as managing it without spatial data. The complications of spatial data management and analysis should be shielded from the manager, yet flexibility and dynamic behaviour are essential ingredients in a successful tool. So it seems that what is required is a foundation for spatial data management and basic geometric analysis that is free of assumptions regarding the nature and use of the data. Built on top of such a foundation would be a specific extension enabling the natural resources manager to find the answers to his or her questions, in his or her conceptual language. It should be clear that metadata would cement the pieces together, providing a conceptual continuity within the tool, and logical continuity between tools or different users. Best of all, the tool should be able to adapt itself and become an extension of the manager, doing his or her things and thinking his or her ways.

3.1 Metadata revisited

Metadata is the logbook of the database. The current international efforts in the development of metadata standards fall short of addressing most of the issues mentioned above. Metadata should be extended, conceptually and in content and purpose, to account for the user's interaction with spatial data. From its original purpose of publishing characteristics of available data sets to a wider audience, it should develop into a true tool for the local user, with a much more elaborated module of data quality control and lineage, including the characteristics of the processes that produced the data set. Such an extended metadata system would enable a basic form of intelligence in spatial tools, to the extent that an automatic *a priori* assessment could be made of the adequacy of certain data for a specific process, or, inversely, to rule out certain processes on the basis of the available data for the analysis.

Metadata should become a pervasive, central element in GIS, rather than an add-on that can be used or disregarded at will. Figure 1 displays a schematic overview of the central role of metadata in GIS. Metadata is collected for every operation taking place in the GIS, enabling the tracking of the entire lifetime and different identities of every piece of original data entering the system. This may seem like an overkill, and indeed many users have not used even current metadata systems for the burden of collecting and recording the data and for the additional processing and disk space requirements. With regards to the last point, it is easy to see that this objection is defeated by the increasing power of ever-cheaper computers. Furthermore, elaborate metadata systems enable functionality not feasible in 'dumb' systems, thus providing the added value to the compilers of the metadata that current systems scantily offer. The first point is very valid though and needs attention in the development of enhanced metadata systems. A properly designed metadata system, however, is self-enabling, in the sense that the state of an entity can be derived from its previous state and the transformation it was subjected to. The system thus could collect most of the required data automatically during the processing stage. The burden on the user is mostly related to the high-level qualitative description of data sets and the cognitive aspects of the original data entering the system (i.e. do the GPS points entered into the system represent soil pit locations or sightings of some animal species?) and any classifications applied to

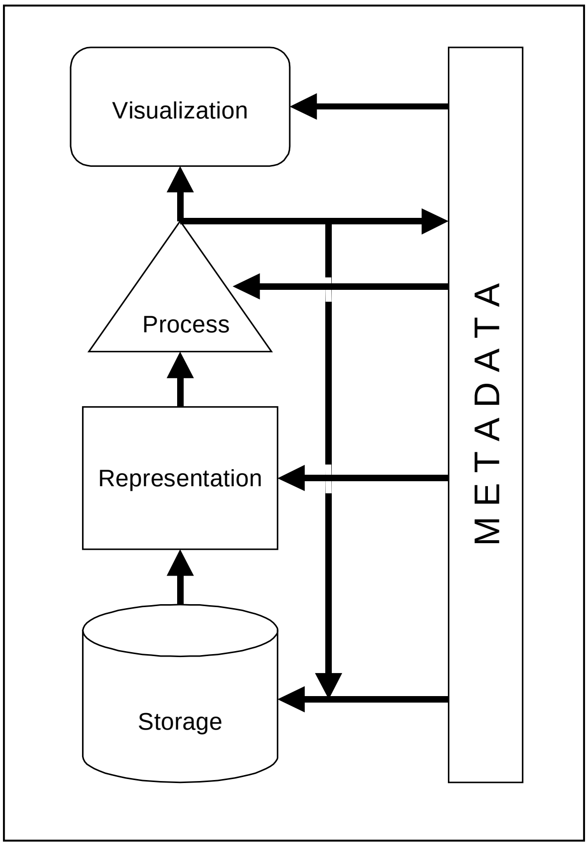

Figure 1. Linking metadata to all the major components of GIS

them.

Such an integrated metadata system could potentially provide the following services to the user:

- **Manage the database** This ranges from keeping track of where data resides to performing background tasks (such as backing up data and maintaining indexes) to balancing the load of the database on the network.
- **Inventory the data** Metadata can be used to make an inventory of available data pertinent to a particular project or matching established criteria of geographic location, content and quality. The user only has to indicate those criteria and need not worry about the representation or physical location of the data.
- **Tune the process** Depending on the criteria established by the user and the quality of the available data a more or less sophisticated algorithm may be applied. The particulars of the process will be stored as metadata, being an essential component in analyzing both the quality of the result and the quality of the process itself.
- **Automate visualization** Particular data require specific types of visualization. This could include projections, ancillary data sets to be displayed or colour schemes, or it could encompass a complete visualization environment to match certain criteria for mapping. The visualization of uncertainty needs special attention, as it is highly subjective to interpretation by the user, the domain expert. While perfectly equipped to manage uncertainty, the domain expert should have a means to communicate his or her conclusions to the system, such that the system may ‘learn’ the relative weight of different expressions of uncertainty in specific contexts, and use this knowledge to potentially reduce uncertainty in future operations.
- **Get to know the application** Perhaps one of the most interesting uses of a comprehensive metadata architecture is the possibility of learning the kinds of operations applied on the data and the purpose for which it is used. This opens up a wide range of potential improvements ranging from automated processing, to improved algorithms, to incremental updating, to design of the physical implementation of the system, *et cetera*.
- **Get to know the user** Analogous to the previous point, the preferences of the users of the system could be learned and the user interface could be adjusted accordingly, tailored to the specific user accessing it. Such adaptability would be particularly beneficial to the casual or non-expert user, which the operators of GIS in NRM will often be. Adaptability of the user interface is since long one of the primary wishes of the user (Davies and Medyckyj-Scott, 1994).

4 A NEW GIS FOR THE LAYMAN

Clearly, the domain expert in natural resources management needs a new GIS. The domain expert cannot continue to be the layman and *trust* the GIS to provide reliable answers to his or her queries. The domain expert will not continue to adapt procedures to the GIS and live with the limitations of a discrete, deterministic view on a continuous, probabilistic environment.

GIS have long had an aura of divinity to the practitioners of geography, to the urban planners, to the telephone network maintenance crews, to the natural resources managers. GIS was the Oracle that provided the answers to complex spatial queries. And given the state of science and technology, this was probably all we could ask for even just five years ago. Science and technology have made important strides since then, yet GIS stayed essentially the same. Notwithstanding the beauty and utility of new functionality such as real-time 3D fly-throughs and internet databases, most commercial systems fail to address the more fundamental issues outlined in this paper. GIS will have to adapt to the user instead of vice versa, it will have to adapt to the data. It should let the domain expert be just that: an expert in soil conservation, forest management, wetland protection. GIS is no longer the Oracle and it is about time it left its temple in Delphi to take its place among the other tools and options available to the domain expert in natural resources management.

Technical expertise in the acquisition, processing and interpretation of spatial data cannot be expected to be available to the domain expert using spatial data for NRM or sustainable development. Providing generic data to the domain expert for use in a generic GIS will, therefore, not be sufficient. Spatial analysis tools for NRM will have to be designed to encompass a complex of data inputs, processing, analysis and interpretation of outputs, where every management situation requires a unique combination of data and analytical functionality (Van Laake, 1999). The increasing complexity of NRM under the current paradigm of multi-purpose, sustainable use of natural resources mandates the analysis of large amounts of data of diverse nature and content. A (semi)automated tool has to be available to shield the domain expert from the complexities of spatial data management and processing, such that he or she can concentrate on specific management tasks as required by the resource condition and the policies regarding its use.

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REFERENCES

Burrough, P.A., 1992. Development of intelligent geographical information systems. Intl. J. GIS, 6(1), pp. 1-11.

Burrough, P.A., Frank, A.U., 1995. Concepts and paradigms in spatial information: are current geographical information systems truly generic? Intl. J. GIS, 9(2), pp. 101-116.

Burrough, P.A., McDonnell, R.A., 1998. Principles of Geographical Information Systems. Oxford University Press, Oxford, UK.

Clarke, D.G., Clark, D.M., 1995. Lineage. In: S.C. Guptill, J.L. Morrison (eds.) Elements of spatial data quality. Published on behalf of the International Cartographic Association by Elsevier Science, Oxford, UK, pp. 13-30.

Davies, C., Medyckyj-Scott, D., 1994. GIS usability: recommendations based on the user's view. Intl. J. GIS, 8(2), pp. 175-189.

FGDC (Federal Geographic Data Committee), 1998. Content Standard for Digital Geospatial Metadata. FGDC-STD-001-1998. FGDC, Washington, D.C.

Glackin, D.L., 1998. International Space-based Remote Sensing Overview: 1980-2007. Can. J. Rem. Sens., 24(3), pp. 307-314.

Goodchild, M.F., 1992. Geographical information science. Intl. J. GIS, 6(1), pp. 31-45.

Hall, C.A.S., LeClerc, G., Van Laake, P.E., 2000. The Derivation and Analysis of National-level Geographical Information: A New Model for Accessibility and a Free Micro-GIS Program. In: C.A.S. Hall, C. León Pérez, G. LeClerc (eds.). Quantifying Sustainable Development: The Future of Tropical Economies. Academic Press, San Diego, pp. 159-175.

Heuvelink, G.B., Burrough, P.A., 1993. Error propagation in cartographic modelling using Boolean logic and continuous classification. Intl. J. GIS, 7(3), pp. 231-246.

Holmgren, P., Thuresson, T., 1998. Satellite Remote Sensing for Forestry Planning – A Review. Scand. J. For. Res., 13, pp. 90-110.

Hootsmans, R.M., 1996. Fuzzy Sets and Series Analysis for Visual Decision Support in Spatial Data Exploration. Faculteit Ruimtelijke Wetenschappen Universiteit Utrecht, Utrecht, The Netherlands.

IMSD, 1996. Application of Remote Sensing and GIS techniques for better land resources management in Kinatthukadavu Block Coimbatore District, Tamil Nadu. In: National workshop on application of Remote Sensing & G.I.S. techniques to integrated rural development, Hyderabad, India, pp. SII.72-SII.85.

Kohonen, T, 1995. Self-organizing Maps. Springer Verlag, Berlin, Germany.

Lagacherie, P., Andrieux, P., Bouzigues, R., 1996. Fuzziness and Uncertainty of Soil Boundaries: from reality to coding in GIS. In: Burrough, P.A., Frank, A.U. Geographic objects with indeterminate boundaries. Gisdata 2. Taylor & Francis, London, pp. 275-286.

Molenaar, M., 1997. The extensional uncertainty of spatial objects. In: Advances in GIS Research II. Proceedings of the Seventh International Symposium on Spatial Data Handling, Delft, The Netherlands, pp. 571-583.

Openshaw, S., Openshaw, C., 1997. Artificial intelligence in geography. John Wiley & Sons Ltd., Chichester, UK.

Prévost, Y.A., Gilruth, P., 1997. Environmental Information Systems in Sub-Saharan Africa. Building blocks towards sustainable development in sub-saharan Africa, paper no. 12. World Bank/UNDP.

UNCED (United Nations Conference on Environment and Development), 1993. Agenda 21, programme of action for sustainable development. United Nations, New York.

Van Laake, P.E., 1999. Spatial data requirements in sustainable forest management: A study in four tropical countries. Forest Assessment and Monitoring Environment, User Requirements Study, Technical Document 5. ITC, Enschede, The Netherlands.

Veregin, H., 1989. Error modeling for the map overlay operation. In: Goodchild, M., Gopal, S. (eds.) The accuracy of spatial databases. Taylor & Francis, London, pp. 3-18.

Wang, F., Hall, G.B., 1996. Fuzzy representation of geographical boundaries in GIS. Intl. J. GIS, 10(5), pp. 573-590.

Westinga, E., Bijker, W., Van Dijk, K., Savenije, H., Symons, H., Heering, J., Nobbe, E., 1999. User needs assessment for spatial forest information: Results and analysis. Forest Assessment and Monitoring Environment, User Requirements Study, Technical Document 4. ITC, Enschede, The Netherlands.

Woodcock, C.E., Gopal, S., 2000. Fuzzy set theory and thematic maps: accuracy assessment and area estimation. Intl. J. of GIS, 14(2), pp. 153-172.