Environmental decisions with spatial process modelling

Samuel Mann
Spatial Information Research Centre
Department of Information Science
University of Otago, PO Box 56, Dunedin,
New Zealand
Phone: +64 3 479 8301
samann@commerce.otago.ac.nz

1 Abstract

This paper first describes the difficulties inherent in supporting a class of environmental problems, those involved in Regional Environmental Decision Making. A set of conceptual criteria are presented along with discussion on how the criteria might be approached. It is shown that a major obstacle is the need for a system that integrates components of Geographic Information Systems with process modelling functions. A new approach, Spatial Process Modelling is proposed. More detailed design criteria for this system are developed which are then used to develop a prototype system. The system is described and benefits and limitations discussed.

2 Introduction

This paper discusses the background, methods and initial testing of a Spatial Process Modelling System. While the system is intended for general use, a case study of a class of environmental problems is described for which current support is poor. These are the issues involved in regional environmental decision making (REDM).

2.1 Regional Environmental Decision Making

Two major forms of issue can be identified in environmental management. The first is that over the siting of particular noxious land uses, the "yes, but not in my backyard" problem. Such problems are suited to traditional decision making and to the array of tools currently available. Opposing groups present their graphs and maps in order to convince decision makers. These conflicts are also well served by bargaining techniques (computerised or not) where a residents group may be able to negotiate the establishment of a park on a corner of a large industrial development. Tools such as geographic information systems (GIS) may be of use here.

Regional Environmental Decision Making (REDM) forms a second group of issues. It is not well served, either by traditional decision making or by the tools used in these processes. These issues are those which are considered to be of regional significance and include decisions about grazing practices, the introduction of alien organisms, the impact of tourism and so on. Mann (1995) has shown that current REDM does not satisfy measures of good decision making (eg. Cleaves 1995).

2.2 Computer Support for Environmental Problems

The development of strategies for improving REDM is poorly supported by current decision support systems. Marr and Benwell (1996) showed that only 20% of local and regional government agencies were performing land use analysis with GIS despite 70% using GIS in the organisation. Data from a survey conducted by the author of NZ resource management practitioners (NZARM) shows that 42% were unsatisfied with current computer support for their work. The development of computer aided support is hampered by the inability to model and understand the complexities of specific environments (Mann and Benwell 1995). These include;

- uncertainty in goals (eg: ‘sustainability’, ‘biodiversity’)
- uncertainty in knowledge, often with conflicting evidence
- a dynamic environment
- importance of varying scale in time and space
- complex processes including feedback loops
- interaction of natural and human environments and the incorporation of policy and ‘precedent’ in decisions.

3 Tools to meet conceptual criteria

Mann (1996) took these perceived difficulties and developed a set of criteria required for development of useful tools for REDM. These criteria are shown in Table 1.

GIS applications are widely used in resource management situations and can be shown to improve performance. Crossland *et al.* (1995) showed that for well structured problems, GIS “makes positive contributions to decision maker performance, as evidenced by lower solution times and greater accuracy” (pg231). It is not clear though how the simple tasks measured by Crossland would generalise to the more complex area of REDM.

Table 1: Conceptual Criteria

1. a toolbox approach to allow flexibility while retaining powerful processing 2. spatially based analysis and display (including functions usually associated with geographic information systems, GIS) 3. process modelling functions 4. emphasis on facilitating human interaction and thinking for both workshop situation and single user 5. ease of use 6. facilitating requirements for organisational decision making.

The author's NZARM survey shows that of a wide range of methods used to represent the environment as part of a decision making process, personal conceptual models and spoken and written conceptual models were the most important. More formal methods, equations, textbook diagrams and programming, were least important. When asked to name the information sources used in their situations, again, a wide range of sources were identified but paper and digital maps were identified as the most frequently used. Decision support for REDM requires a mix of conceptual modelling and spatial analysis. Burrough and Frank (1995) however argued that "there is a large gap between the richness of the ways in which people can perceive and model spatial and temporal phenomena and the conceptual foundations of most commercial geographical information systems" (pg105). Unless this gap can be closed GIS may remain unsuitable for REDM support.

If serious attempts are to be made to manage the environment then appropriate information must be available as to the consequences of any actions. Because most environmental action is irreversible, modelling provides a powerful way of non-destructively testing actions and outcomes. There are many examples of simulation models being used in environmental decision making and both models and model*ling* can be seen to have several benefits.

A first benefit is in prediction. Simulation predictions (Kirchner 1994 prefers 'system characterisations') can assist decision makers in testing the potential outcomes of management alternatives. Often, as Pandey and Hardaker (1995 pg443) argued, "modelling results may bring the reality home to decision makers". In this vein, Ball (1994) considers a good model as "one that is capable of reproducing the observed changes while producing insight into the dynamics of the system".

A second benefit of modelling is in the generation of 'new' knowledge. Leimback (1994) describes a system of simulation based knowledge acquisition where, if in model development a piece of knowledge is missing, smaller model runs are initiated to populate the larger models.

A third, possibly more important benefit of modelling is the modelling process itself. Holling (1978) presented a process called Adaptive Environmental Assessment and Management (AEAM) that "uses the construction of dynamic models as an intellectual device to help people clarify issues, communicate effectively about shared concerns and explore objectively the construction of alternative policy options" (Walters 1986, pg43). Grayson *et al.* (1994) described workshops where the aim is to develop a simulation model which can be used to evaluate the effects of various management options. The model is the tangible outcome but "the modelling workshops are shown to be of primary importance" (pg245), indeed there is no method of saving results from the model. Key benefits include the atmosphere of ownership of the problem and solution, the use and critical appraisal of available information and that "capabilities and limitations of model are well understood by all...a different approach compared to many computer simulations of natural systems wherein the assumptions and limitations are often concealed rather than revealed" (pg 251).

4 Development of design criteria

4.1 Integration

There have been many calls for the integration of modelling and spatial information systems. So what are the obstacles to this development?

Data integration is identified by a number of authors as a recalcitrant factor. For example Kirchner (1994) argued that the shift from static models (including maps) to models where the structure is not predefined has implications for data requirements. Organisation and bookkeeping of inputs and outputs must take on increased importance. Coleman *et al.* (1994) suggested that "transfer of data between ecological models and GIS can be time consuming, and requires unique solutions for each model-GIS interaction" (pg398) but this is not a very practical solution. A further problem is the complexity and size of processing required by models containing spatial and temporal aspects. Coleman's solution was to use distributed processing over several UNIX machines but this severely limits the portability of systems. At present this extended processing time may be a problem that we have to live with.

Despotakis *et al.* (1993) argued that GIS is primarily data driven while modelling is essentially process driven. This results in conflicting paradigms, GIS has space as the independent variable (ie. is frozen in time) while modelling is the converse (frozen in space). They concluded that that there is a "missing node between the field of GIS modelling and non-spatial modelling which would be necessary to integrate the benefits from both fields in a dynamic sense" (pg236). This view is supported by Nyerges (1992) who identified emphasis on content and structure for GIS and content and process for modelling.

A further problem is what Steyaert and Goodchild (1994) described as the cumbersome interfaces of GIS. This however is more of an issue than just the 'front end' of GIS and can be traced back to the previous discussion about emphasis. In describing the gap between what can be represented in GIS and the perception and modelling abilities of people, Burrough and Frank (1995) argued that the reductionist approach employed by GIS is sensible when dealing with simple, easy to combine abstract objects but is not suited to the natural world. A major conflict is the way in which dynamic processes are represented. An environmental scientist might produce a map of evaporation on a particular day but would find it harder to use a GIS to represent the processes involved in evaporation. This would be needed to predict evaporation or to model the effects on rainfall of a revegetation programme.

There is then a mismatch in interface, in data organisation and in general approach. Most of these problems come down to a difference in what is represented in terms of perceptions; pattern (data) or process (dynamics). This should not be an overwhelming obstacle, much of Geography could be described by the interaction of these themes (see Chapman 1979). The task then is to develop a GIS/model hybrid that best mixes the advantages of both pattern and process while overcoming the inherent conflicts. Such a system is referred to as Spatial Process Modelling (Figure 1). This figure can be seen as a metaphor for the problem at hand. Environmental problems occur in the real world. Both process modelling and spatial model are projections away from the real world but as previous discussion suggests, the two projections are in different directions. It is proposed that a modelling system which combines the two approaches will better approximate the 'real world' and allow improved decision making.

4.2 Design Criteria

This section examines approaches to modelling with the intention of developing design criteria for Spatial Process Modelling. Rather than characterise integration according to coupling intensity (*sensu* Goodchild and Wise 1992) or method of integration (*sensu* Lilburne 1996), the focus here is on the degree of flexibility in modelling.

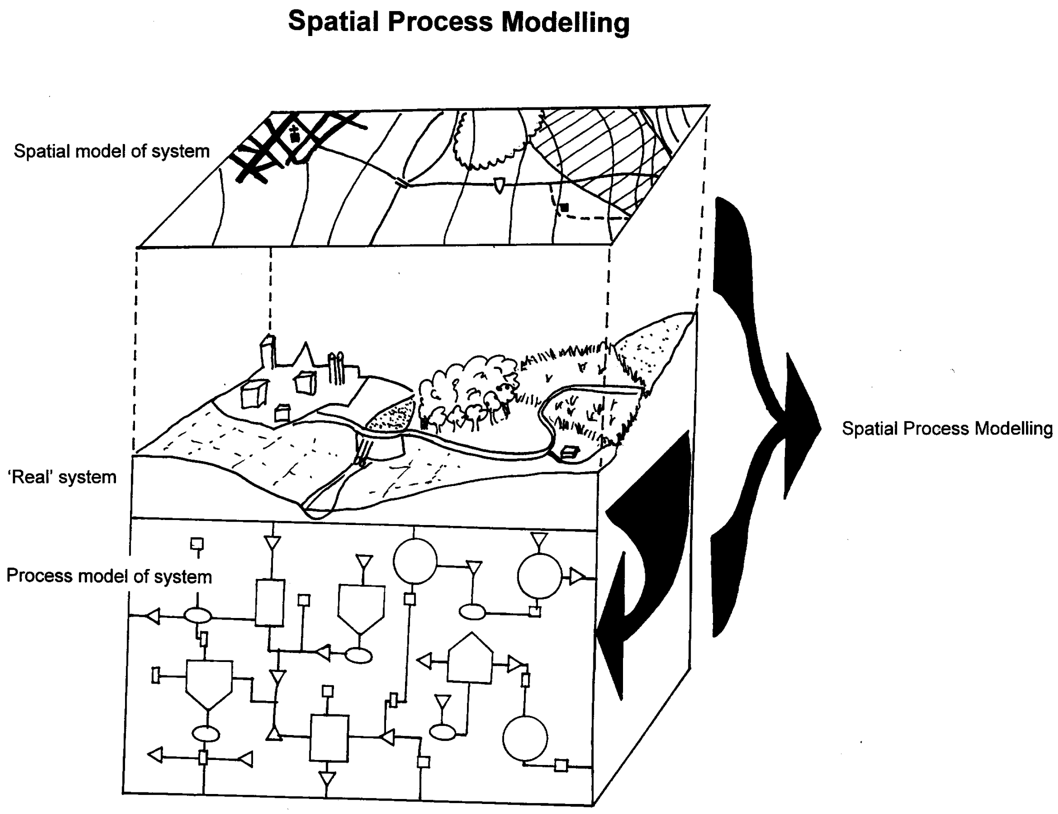


Figure 1: Spatial process modelling integrates GIS and process modelling

There are many successful models in environmental management. Most however are 'preformed', allowing the user to examine a limited number of options. These systems are really Decision support systems in the traditional sense of providing answers to predictable questions (eg Geraghty 1993). The rigid structure however eases the problems of data management and allows sophisticated display (Bishop 1995).

At the other end of the scale are approaches that rely on an ability to write code within a formal programming language. The AEAM workshops described by Grayson *et al.*

(1994) are examples of this. While participants are encouraged to feel an ownership of the model, they are in fact, separated from it, being forced to work through a programmer. Further, it is difficult for participants to get an overall feel of the model as it is implemented in code (at present QuickBasic, Grayson *pers comm* 22/1/96).

The ECO-LOGIC program of Robertson *et al.* (1991) aimed to provide assistance in these problems of comprehending model structure and writing code. Their approach was for the program to ask questions to build the model from key points, for example: 'what do rabbits eat?' and 'how is growth represented?'. Templates are then used to write code (Prolog) that can be compiled and run as a simulation. The disadvantages of this approach are that it is domain specific and that information used to describe models is often too vague for code generation. The models also have to fit into a relatively predictable structure, a user is unable to deviate from the predefined structure.

Lowes and Walker (1995) described a high level language that allows a user to specify a model structure using pseudo-English. They found that this "high level, domain specific task or macro language" (pg2) was sufficient for representing the decision makers model of problems and enabled generation of a tool (code). However the task language was "too difficult" so they now favour diagrammatic approaches.

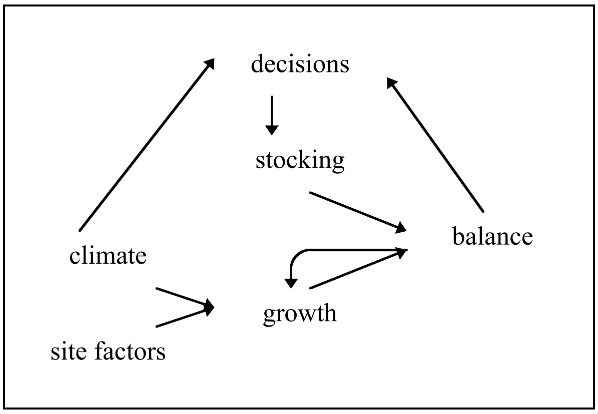


Figure 2: A simple model of a farming system

Diagrammatic approaches have an advantage in that they are closely aligned with conceptual diagrams. Such diagrams in varying forms can be found within the pages of textbooks on almost anything, from simple flow charts of water cycles to complex representations of agroecosystems. Figure 2 shows a model of a farming system. While very simple, this model could be used to facilitate discussion among stakeholders. Farmers for example might wish to add a link between the land (site factors) and farming decisions.

With computerised diagrammatic techniques, diagrams such as Figure 2 can become much more powerful. Dynamic modelling packages such Stella (HPS 1990) facilitate the development of system models through a toolbox library system of model components. Although the model appears sketched, the package allows the users to run simulations to examine the effects of varying parameters and/or model structure. The user, then, is separated from the business of generating code, but still has access to a powerful and flexible modelling system. The problem though, is that these modelling systems are presently aspatial.

A list of design criteria is given in Table 2. It is argued that development based on these criteria while still meeting the broader objectives of Table 1 will make a useful support system for REDM.

Table 2: Design Criteria

- **Visual**: The system must be easy to use with a Graphical user interface.
- **Interactive**: The user must be able to develop scenarios interactively.
- **System dynamic modelling**. There are three components to this criteria.

1. the model must be able to support a systems approach
2. the system and the systems it represents are dynamic which requires flexibility in design and use
3. the use of modelling. The system must support the development of models rather than fixed models.

- **Spatial:** The system is concerned with the management of the environment. The support of environmental decisions requires an ability for spatial manipulation and presentation.
- **Model database**: A database for model structure (as distinct from the environmental data).
- **Integrated**: Models are not inherently spatial, in fact most are aspatial and may be represented in modelling packages such as Stella and Extend. The environment is spatial and is represented within geographic information systems. The linking of these two approaches should be integrated by the system such that the model components include the spatial objects. This integration is a fundamental criterion.
- **Generic**: The system should be generic. That is, the system should operate as a toolbox independent of the domain.
- **Portable and PC based**

5 Spatial Process Modelling System

5.1 Overview

This section describes a prototype implementation of a Spatial Process Modelling System. The SPMS essentially inserts map objects directly into a Stella-like visual modelling toolbox. This step has resulted in a powerful yet flexible tool but has also raised many methodological issues. First an overview of the system is presented from the users perspective. This is followed by a description of the structure of the system. Benefits and limitations of the current implementation are also highlighted.

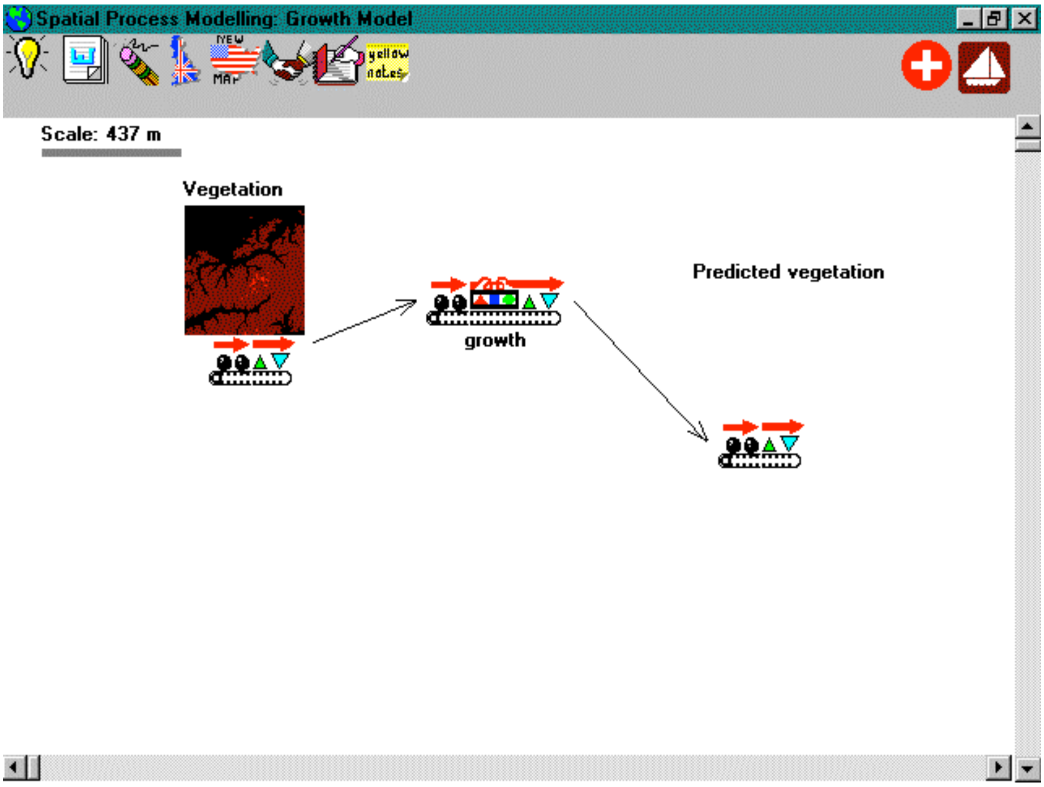


Figure 3: Growth model under development

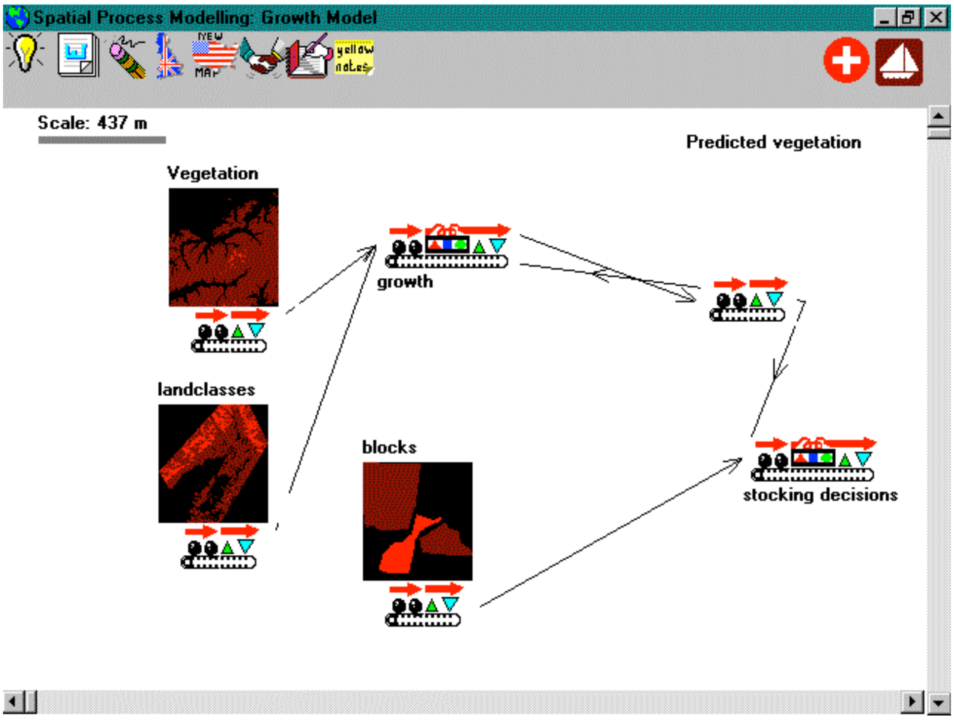


Figure 4: More complex growth model

In the SPMS users build process diagrams interactively (see Figure 3 and Figure 4). At the core of the program, the GIS analysis[1] and modelling functions are combined. Within a graphical environment, process models (emulating objects) are linked together visually. Also available to form part of the model are spatial objects, with inputs and outputs. Objects may be joined to form complex structures allowing feedback mechanisms.

---

[1] GIS input and preparation are done elsewhere (eg Idrisi) It would also be desirable to use methods such as the federated schema suggested as part of Lake's (1996) electronic round table for environmental management.

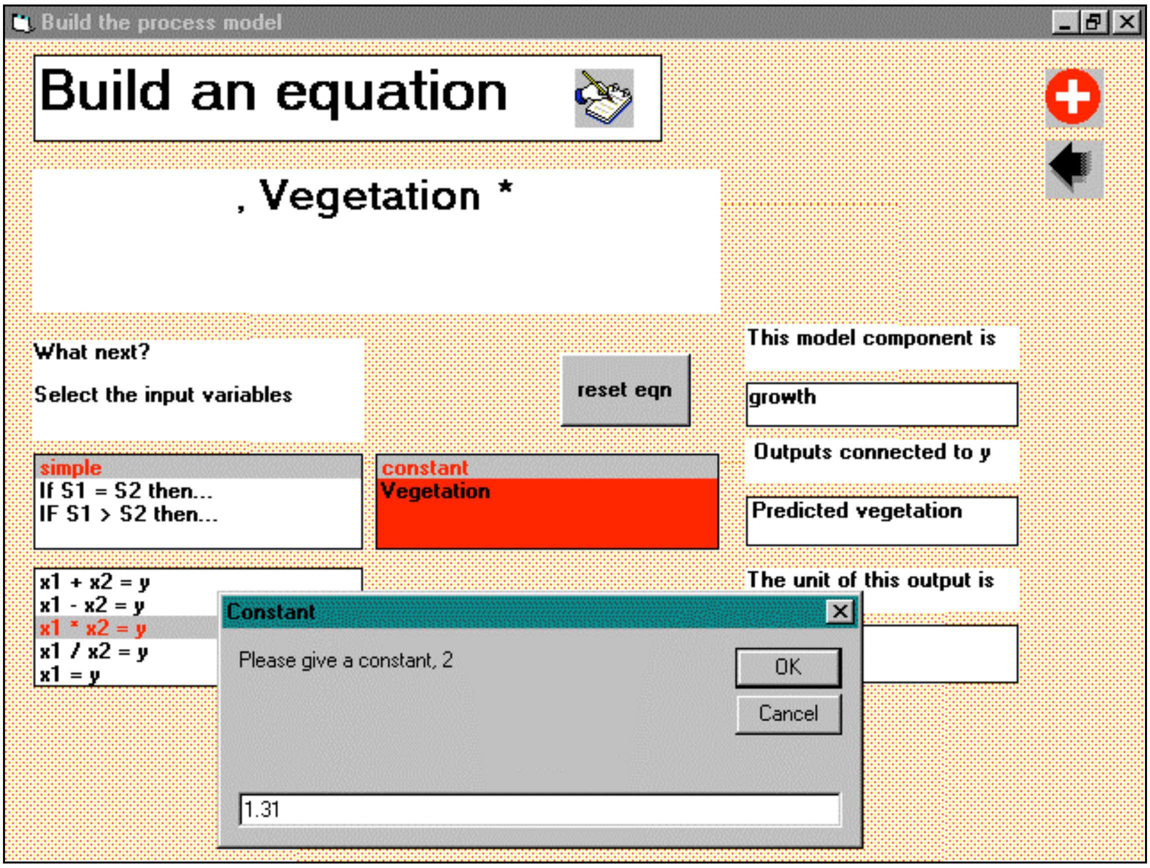


Figure 5: Equation builder, presents linked components and leads user through equation definition.

Lines are drawn linking the objects and then the equation for each process model is defined according to the inputs and outputs. The equation builder (Figure 5) presents the links connected to the process component and leads the user through defining the equation. In the current implementation this equation is relatively simple, for example add 5 to input 1 when input 2 = 10. It would however be beneficial to include more complex geographical operators (eg Albrecht's 1996 Universal GIS Operators) and more complex conditional statements. For example in Figure 4 different decisions may be

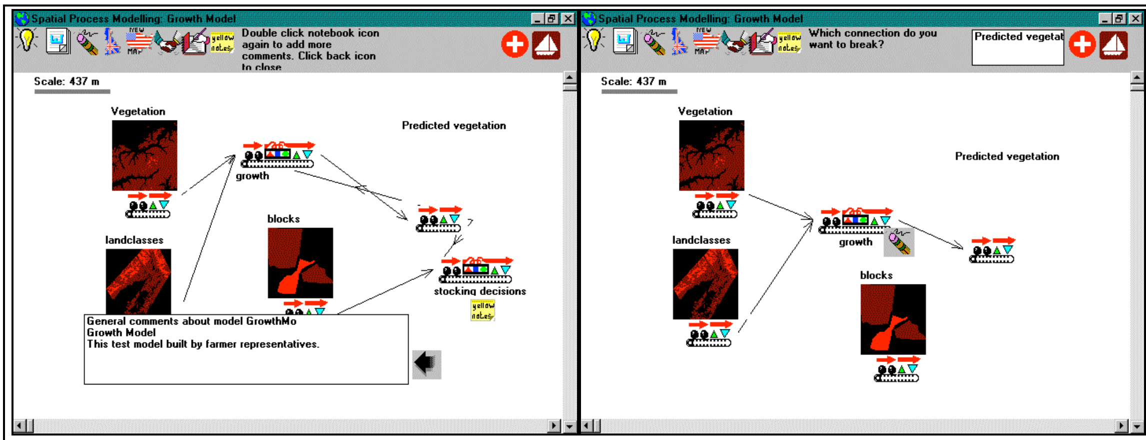


Figure 6: The system is flexible and allows deletion of links and whole components. Annotations may refer to the whole model or to specific components.

made for each farm block but the SPMS cannot currently deal with this. A method of including tabular data is needed to achieve this goal.

The equation may also be annotated with any assumptions made, for example, 'this is how tussock grass responds to burning, I know that is different in very dry years' (Figure 6). This has the duel advantage of clearly laying out assumptions, and in directing areas where further research is needed. Including technical details in the model but hiding them from view may also facilitate the integration of research findings from a number of disciplines.

5.2 Technical Description

The SPMS has four major components, the interface control, model structure tables, model launcher and report generator (Figure 7).

The system was developed in Visual Basic (4 Professional) as this encompassed the values of rapid software development, is PC based and is compatible with a large range of existing software (notably MS-Access and MS-Word). Access is used for the model structure data while OLE links to MS-Word allows generation of reports from modelling sessions.

The main form (at the top right of Figure 7) has an expandable drawing space and a toolbox of icons. At the start of a session a dialogue box asks for the model name, which is used to generate a new Access table for that model. All model components are then represented by a row in that table. Fields are shown in Table 3. The object type refers to whether the component is a process or map object. A further two object types, tabular and chart are intended in future development. The interface controller uses the screen coordinates to position each component and associated links. The apparent redundancy

Table 3: Model structure fields
Session name
Model
Index number
Object name
Object type
Unit
Map file name
Screen positional data
Links
Inputs (from model number)
Outputs (to model number)
Line references
Equation information
(equation type, constants, referential index values)

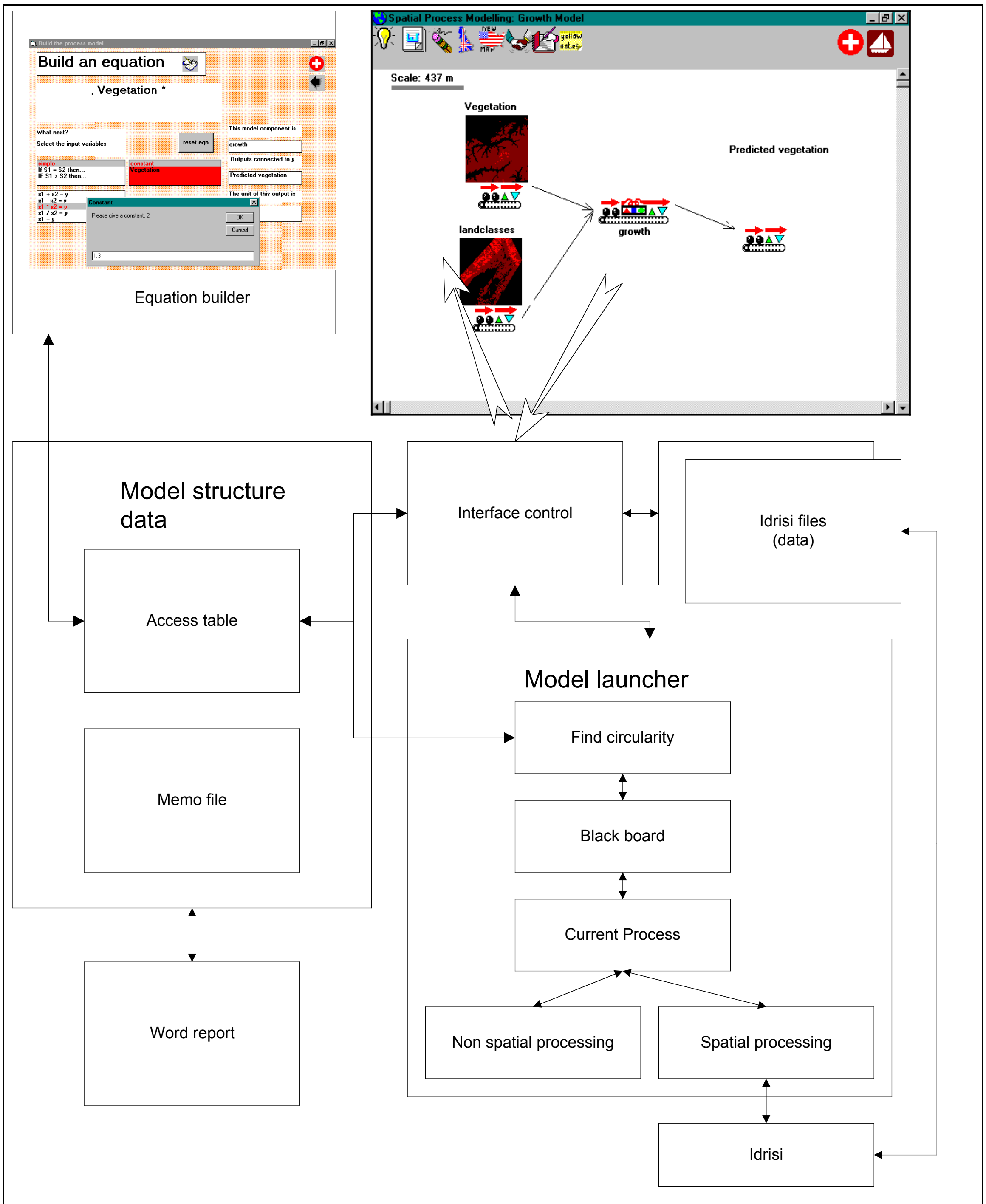


Figure 7: SPMS Structure

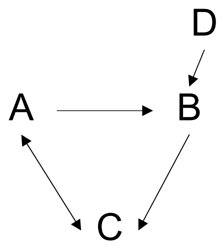
in the input and output links is to overcome a limitation in Visual Basic in that lines do not have properties enabling identification and selection. As Figure 6 shows, links can be selected and deleted, as can whole model components.

The model can be launched at any stage (but will not give results unless links are complete). This will 'compile' the model and run it. This is performed by a series of functions and arrays that are used to interpret the model structure table. Figure 8 shows the structure of the arrays needed to launch a simple test model structure. For the moment, assume that all components are aspatial and that equations have two components without conditional operators. This then is a relatively simple feedback loop with equations assigned to each process. The first function moves through the model structure ('Modelboard array') following the links. Component 'A' requires a constant; '20' and component 'C'. This means 'C' must be either initialised or computed before 'A'. 'C' is found to require 'A' which means the model contains circular references, 'C' must be initialised and the user is so prompted. When all references are resolved, the model is reordered onto the 'Blackboard array' so it can proceed. The 'Current process function' then moves through each component in turn performing calculations and feeding the values back to the 'Blackboard'. In this case all processing is performed within the SPMS but if one or more components are spatial then Idrisi (Eastman 1992) is used. This is made more complex as spatial components feed through the model. In the example case, if 'D' was a map object, three methods of performing calculations are required; both aspatial, one spatial one aspatial, and both spatial (see Table 4). Calculations performed in Idrisi are driven for each 'Current process' in turn by command line exported from SPMS via .bat and .pif files. This is transparent to users.

Also note from Table 4 that by the end of two iterations, five maps the size of the original represented by 'D' have been created. This can quickly lead to a data storage problems so in the current implementation, only the first and last values are stored. When processing is complete control is returned to the interface control and any changed maps are updated.

Testing with various structures has shown that the prototype SPMS can manage structures such as that represented in Figure 8, and even more complex combinations of test configurations with moderate success. Unfortunately when applied to more realistic cases (such as Figure 4) there is less success. Firstly as already established, the equation builder does not accept complex or tabular concepts. Second, the growth model has links from both 'predicted vegetation' and 'vegetation'. Intuitively the model should use the 'vegetation' on the first cycle and 'predicted' thereafter, but is currently unable to do this. What is needed is a method of including the temporal dimension into the model structure and expressing this in both the equation builder and the launch processor.

Figure 8: Array structure to launch test model structure



A= C + 20
B = A/D
C = A-B
D = 20
i = 2

Model Board				
Ref	x1	x1type	x2	x2type
A	C	ref	21.	Cons
C	A	ref	B	ref
B	A	ref	D	ref
D	20	cons	-	-

Blackboard (t=0)			
	Current Value	Current type	Current time
A		nonspatial	0
D		nonspatial	0
B	40	cons	0
C	150	Initialised	-1

Current component	Time	x1	x2	operator	returns
C	0	150	na	=	150
A	1	C	20	+	170
D	1	40	na	=	40
B	1	A	D	/	5.67
C	1	A	B	-	164.33
A	2	C	20	+	184.33
D	2	40	na	=	40
B	2	A	D	/	4.61
C	2	A	B	-	179.72

Table 4: Effect of Component 'D' being spatial

Current component	t	x1	x2	op	returns	Performed by
C	0	150	na	=	150	SPMS
A	1	C	20	+	170	SPMS
D	1	spatial	na	=	map_D	na
B	1	A	D(spatial)	/	map_B1	Idrisi Scalar
C	1	A	B(spatial)	-	map_C1	Idrisi Scalar
A	2	C(spatial)	20	+	map_A2	Idrisi Scalar
D	2	spatial	na	=	map_D	na
B	2	A(spatial)	D(spatial)	/	map_B2	Idrisi Overlay
C	2	A(spatial)	B(spatial)	-	map_C2	Idrisi Overlay

6 Discussion

Difficulties encountered when dealing with the environment result in inadequate regional decision making. This situation is not helped by the current generation of computerised aids. Conceptual criteria have lead to a desire to combine GIS and process based modelling in a way that is useful for decision making. This has lead in turn to design criteria for a Spatial Process Modelling System. A prototype development of such a system has shown that while most of the criteria are met there remains computational difficulties in developing a functional system. The three most crucial of these are needs for an explicit representation of time, an improved equation builder with better conditional statements, and the incorporation of tabular data. Once these features are operational, more long term goals include the development of a hierarchical representation, modular links to other modelling tools, and data management. Work on the representation of error with assessments of sensitivity to variation in model components would also be beneficial.

When these problems are overcome the SPMS with feedback loops and the ability to modify model structure within a spatial paradigm may become a useful tool in Regional Environmental Management. The system relies on the successful integration of spatial processing and display with the characteristics of system dynamic modelling.

7 References

ALBRECHT, J. H. 1996. Universal GIS operators for environmental modelling. Third International Conference Integrating GIS and Environmental Modelling, Sante Fe, NCGIA.

ALBRECHT, J. H., JUNG, S., MANN, S. 1996. VGIS-- a GIS shell for the conceptual design of environmental models. GISRUK'96, Canterbury UK.

BALL, G. L. 1994. “Ecosystem modelling with GIS.” *Environmental Management* 18: 345-349.

BISHOP, I. 1995. Creating an interactive immersive decision environment: linking modelling to visualisation. Proceedings of the 23rd Annual International Conference of the Australasian Urban and Regional Information Systems Association Incorporated, Melbourne, AURISA. 474-482

BURROUGH, P. A. AND FRANK A. U. 1995. “Concepts and paradigms in spatial information: are current geographical information systems truly generic.” *International Journal of Geographic Information Systems* 9 2): 101-116.

CHAPMAN, K. 1979 *People, pattern and process: an introduction to human geography*. London, Edward Arnold.334

CLEAVES, D. A. 1995. "Assessing and communicating uncertainty in DSS." *AI Applications* 9 (3): 87-102.

COLEMAN, M. B., BEARLY, T. L. BURKE, I.C. AND LAUENROTH, W.K. 1994. Linking ecological simulation models to geographic information systems: an automated solution. *Environmental Information Management and Analysis: Ecosystem to Global Scales* Eds. W. K. Michener, J. W. Brunt and S. G. Stafford. London, Taylor and Francis. 397-412.

CROSSLAND, M. D., WYNNE, B. E. AND PERKINS, W.C. 1995. "Spatial decision support systems: an overview of technology and a test of efficacy." *Decision Support Systems* 14(3): 219-237.

DESPOTAKIS, V. K., GIAOUTZI, M. AND NIJKAMP, P., 1993. Dynamic GIS models for regional sustainable development. *Geographic Information Systems: spatial modelling and policy evaluation* Eds. M. M. Fischer and P. Nijkamp. Berlin, Springer-Verlag. 235-261.

EASTMAN, J. R. 1992. "IDRISI: A grid based geographic analysis system." *Clark University Graduate School of Geography.*

GERAGHTY, P. J. 1993**.** "Environmental assessment and the application of expert systems: an overview." *Journal of Environmental Management* 39: 27-38.

GRAYSON, R. B., DOOLAN, J. M. AND BLAKE T. 1994. "Applications of AEAM (Adaptive Environmental and Management) to Water Quality in the Latrobe River Catchment." *Journal of Environmental Management* 41: 245-258.

GOODCHILD, M. AND R. H. S. WISE 1992. "Integrating GIS and Spatial Data Analysis: Problems and Possibilities." *International Journal of Geographical Information Systems* 6(5): 407-423.

GROSSMAN, W. D. ANDEBERHARDT S. 1994. Geographic information systems and dynamic modelling: potentials of a new approach. *Innovations in GIS* Ed. M. F. Worboys. London, Taylor and Francis. 167-180.

HIGH PERFORMANCE SYSTEMS 1990. Stella II. Hanover, New Hampshire.

HOLLING, C.S, (ED). 1978. Adaptive environmental assessment and management, International Institute for Applied Systems Analysis. pg377

KIRCHNER, T. B. 1994. Data management and simulation modelling. *Environmental Information Management and Analysis: Ecosystem to Global Scales* Eds. W. K. Michener, J. W. Brunt and S. G. Stafford. London, Taylor and Francis. 357-375.

LAKE, R. 1996. Electronic round table: a contribution to co-operative land management. GIS Applications in Natural Resources. M. Hect, H. Dennison-Parker and A. Shortreid, GIS World**:** 66-74.

LEIMBACK, M. (1994). "Expert system-model coupling within the framework of an ecological advisory system." Ecological Modelling **75/76**: 589-600.

LILBURNE, L. 1996. The Integration Challenge. SIRC'96: Proceedings of the 8th Annual Colloquium of the Spatial Information Research Centre, University of Otago, University of Otago.

LOWES, D. AND WALKER D. 1995. Environmental Management: Opportunities and Challenges in the Application of AI. Proceedings of the Workshop on AI and the Environment: Eighth Australasian Joint Conference on Artificial Intelligence, Australian Defence Force Academy, Canberra, University College, University of New South Wales. 1-11

MANN, S. 1995. "A Case Study in Decision Making." *Environmental Perspectives* 8(August):1-4

MANN, S. 1996. Spatial Process Modelling for Regional Environmental Decision Making. SIRC'96: Proceedings of the 8th Annual Colloquium of the Spatial Information Research Centre, University of Otago, University of Otago.

MANN, S. AND BENWELL G. L. 1995. GIS in environmental management. AURISA/ 7th Colloquium of the Spatial Information Research Centre, Palmerston North, NZ, 295-310

MARR, A. J. AND BENWELL G. L. 1996. "The evolution of the use of GIS in New Zealand Local Government." New Zealand Surveyor(286): 30-35.

NIELSON, N. R. (1991). Application of artificial intelligence techniques to simulation. Knowledge-based simulation - methodolgy and application. P. A. Fishwick and R. B. Modjeski. New York, Springer-Verlag. **4:** 1-19.

PANDEY, S. ANDHARDAKER J. B. 1995**.** "The role of modelling in the quest for sustainable farming systems." *Agricultural Systems* 47: 439-450.

ROBERTSON, D., BUNDY, A. MUETZELFELDT, R. HAGGITH, M. AND USCHOLD, M. 1991**.** *Eco-logic: logic based approaches to ecological modelling*. Cambridge MA, MIT Press.

STEYAERT, L. T. AND GOODCHILD M. F. 1994. Integrating geographic information systems and environmental simulation models: a status review. *Environmental Information Management and Analysis: Ecosystem to Global Scales* Eds. W. K. Michener, J. W. Brunt and S. G. Stafford. London, Taylor and Francis. 333-355.

WALTERS, C.J.. 1986. Adaptive Management of Renewable Resources. New York, MacMillan. pg374