Modelling change in state of complex ecological systems in space and time: an application to sustainable grazing management

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Abstract: Meeting the challenge of sustainable development requires substantial advances in our understanding of the interaction of natural and human systems. The emerging ecosystem management paradigm of multiple stable states, non-linear systems behaviour, discontinuous change, self-organisation and multiple development pathways has major implications for when and how change in complex systems occurs and how it can be managed. It also poses considerable challenges for modelling the structure and function of natural and human management systems including fundamental constraints relating to: scaling mismatches, synthesis of non-homogeneous information, multi-scaled system interactions, complex management systems, uncertainty in causal relationships, assessment of trade-offs, and validation. This paper examines how a decision support system (DSS) for sustainable grazing management, called Landassess DSS, attempted to deal with some of these issues through an integrated systems approach to DSS development. This approach utilised object-oriented techniques, knowledge-based systems, and a state-and-transition model framework in a spatial context to model the critical change processes. It provided for the identification of the major driving factors and constraints to change in rangeland systems, as well as the assessment of the likely tradeoffs between resource sustainability and economic production at a scale relevant to management decision-making (i.e. paddock or property).

1. INTRODUCTION

Questions about change in ecosystems have engaged the attention of ecologists for many years. Contemporary theories support the concept that complex ecosystems possess multiple stable states [eg. Westoby *et al.*, 1989] and their development is characterised by non-linear systems behaviour, discontinuous change, self-organisation, and multiple development pathways [eg. Holling, 1995]. This emerging paradigm of ecosystem management has far reaching implications for when and how change occurs and can be managed. It also poses considerable challenges for modelling the interaction of ecological and human systems and assessing the implications for sustainable development.

The need to understand change processes and their potential impacts on the sustainability of rangelands is becoming particularly critical with increasing public demands for improving the way rangelands are used and managed, and the introduction of legislation in some Australian States requiring landholders to demonstrate sustainable use of the pastoral resource. There is, however, a lack of a broad consensus of opinion amongst policymakers, industry advisers and enterprise managers on the meaning of sustainability in rangeland pastoral systems. This raises an opportunity for model-based decision support tools to provide a mechanism for focussing the debate on the concept of sustainability in extensive grazing management systems at scales relevant to management decision-making (i.e. paddock, property).

This paper presents a modelling approach that addresses these issues through an integrated knowledge-based spatial decision support system. It describes how models, knowledge bases, natural resource, cadastral and other data are integrated and used to assess the environmental and economic trade-offs associated with alternative management scenarios in large spatially variable paddocks. We then discuss the implications of the modelling approach for other applications.

2. THE ISSUE: SUSTAINABLE DEVELOPMENT

2.1 Assessing Sustainability

Although the concept of sustainable development is commonly used, its meaning is so diffuse that it lends itself to widely varying interpretations. Firstly, it needs to be both spatially and temporally defined; what is sustainable at one scale may not be at another, what is sustainable in the short term may not be in the long term. Secondly, in the context of rangelands pastoral enterprises, a common element of most definitions is the dual recognition that pastoral production enterprises need to be economically viable, and the underpinning processes ecologically viable. Thirdly, the complex character of the concept of sustainability means that it needs to be examined in terms of a wide range of scenarios and multiple outcomes to explore the range of viable management options.

2.2 Modelling Constraints

There are a number of common constraints to modelling the structure and function of complex pastoral ecosystems and the impact of the interaction with human management systems. These include:

- *Scaling mismatch*: there is a common mismatch between the scale and character of the problem and the available analytical approaches or empirical data. For example, there is frequently much small homogeneous plot experimental data on the interaction of the pasture resource and grazing management practices, but the context required to be addressed for sustainable development is large spatially heterogeneous landscapes.

- *Synthesis of non-homogeneous information*: the relevant data, information and knowledge may vary significantly in terms of type, completeness, precision, and spatial and temporal scale of relevance. This poses significant difficulties and suggests that a multi-method approach to data integration and analysis will be required.
- *Multiscaled systems interactions:* foraging animals, environmental systems, and human intervention function and interact at different spatial and temporal scales. Modelling the interactions requires a capability to model across a range of scales (eg. point, paddock, property).
- *Complex grazing management systems:* the relationship between the state of the system, the level of resource use, grazing management practices, and the resulting impacts on the natural resource base are neither simple or uniform. This requires the utilisation and integration of a range of information technologies (eg., geographical information systems (GIS), database management systems (DBMS), knowledgebase systems (KBS)). An analytical framework is also needed that can capture and integrate qualitative and quantitative information from diverse sources, and can also handle incomplete knowledge and a range of model types.
- *Uncertainty in causal relationships:* complex systems are characterised by long time horizons with many intervening events, high variability, and complex feedback loops such that it is often difficult to clearly define cause and effect. This leads to significant uncertainty which needs to be recognised and managed [Funtowicz and Ravetz, 1990] in any scenario analysis.
- *Difficulties of assessing tradeoffs*: pasture management impacts on the land resource generally vary with specific land types and will be spatially variable within a paddock. However, pasture management practices are typically applied at an individual paddock level, while the economics of pastoral management generally relate to the whole property, and are difficult to disaggregate to a single paddock. This creates difficulties in modelling environmental and economic trade-offs.
- *Difficulty of empirical validation*: controlled and replicated experiments to validate predictions are impossible to perform in large scale systems or within acceptable timeframes. A range of techniques will be needed to validate different levels of modelling.

The following section describes a decision support system (DSS) for assessing sustainable grazing management within spatially variable paddocks. It examines the approach used to handle some of these modelling issues.

3. LANDASSESS DSS

3.1 The Product

Landassess DSS [Lowes and Bellamy, 1994; Bellamy *et al.*, 1996] was developed in collaboration with agencies responsible for pastoral land management in the Northern Territory (ie. Department of Lands, Planning and Environment, and the Department of Primary Industry and Fisheries). It is designed to assist policy makers, extension and industry advisors, and researchers to:

1. assess spatial variability in the current state of pasture health (i.e., vegetation state and soil erosion risk) of a grazing management unit such as a paddock or property;
2. formulate "what if" scenarios to assess grazing management options in terms of the likely changes in vegetation state and soil erosion risk within the management unit, over time; and
3. evaluate the implications for cattle production and profitability for each scenario.

Landassess DSS has been implemented using the object-oriented knowledge base shell, Level 5 Object [Information Builders Inc.], ARCView [ESRI Inc.] is used to provide the GIS capability and compatibility with the ARC/INFO GIS, and Microsoft Windows Graphical User Interface provides a consistent, interactive and simple user interface. The system design and DSS functionality have been described in Bellamy *et al.* [1996] and Lowes and Bellamy [1994]. In this paper we focus on the approaches to modelling the structure and function of the pastoral system and its interaction with human intervention.

3.2 DSS Design

3.2.1 An Integrated Systems Approach

Landassess DSS takes an integrated systems approach to IT development by "coupling" a number of information technologies which allow for a range of heterogeneous data, knowledge and models to be accessed, linked and analysed. It integrates KBS, DBMS, GIS and simple scientific and economic models as illustrated in Figure 1. This approach takes advantage of the spatial, temporal, and other analytical strengths of these alternative technologies to facilitate the modelling of complex rangeland ecosystems and for the evaluation of alternative management scenarios.

3.2.2 Integrating paradigm: object-orientation

An effective integrated systems approach requires a suitable integrating paradigm. Traditional database design is concerned with identifying and explicitly representing the properties and attributes that characterise the system state itself. The new ecosystem management paradigm requires the representation of multiple stable states, multiple pathways, and the detection and prediction of change. The software engineering technique of object orientation [Bobrow and Stefik, 1986] provides the ability to model real world features with corresponding knowledge-base and software objects. The attributes and behaviour of the objects can be encapsulated in the knowledge base and software representations. Landassess DSS uses object orientation as a powerful and intuitive method for representing and integrating knowledge and data, process models, and spatial information relating to the interaction of the rangeland pasture ecology and human management systems. Through the integration of appropriate methodological tools (e.g. GIS, DBMS, models, KBS), the object-oriented methods also has provided for the development of an efficient, flexible and easy to use integrated DSS product.

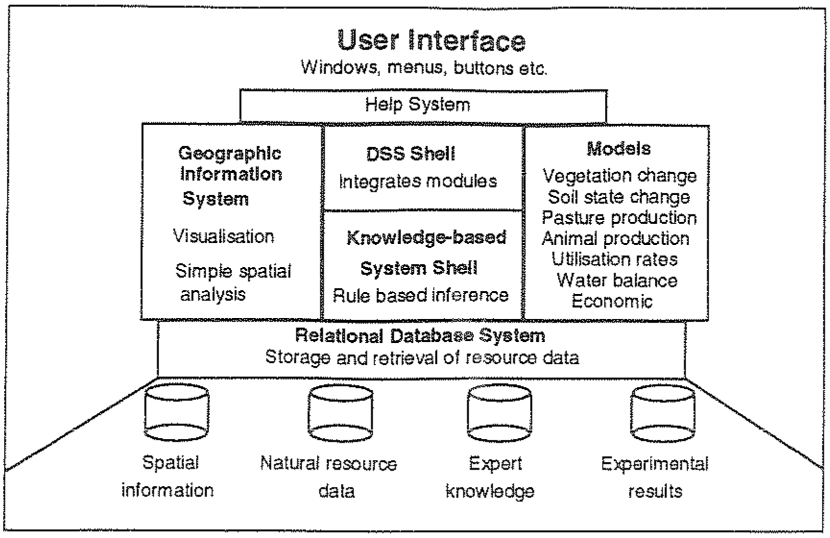

Figure 1: Integrated System components and functions in Landassess DSS [adapted from Bellamy *et al.*, 1996].

3.2.3 The Models Base

Landassess DSS utilises a variety of different models to undertake a range of different DSS tasks [see Bellamy *et al.*, 1996]. These models include:

- Rule-based models (e.g. state-and-transition models of vegetation change, soil erosion risk, animal preference);
- Simple process models (e.g. water balance);
- Simple numerical models (e.g. animal intake, utilisation rate)
- Spatial models (e.g. distance to water, pasture utilisation patterns)
- Regression models (e.g. animal and pasture production); and
- Spreadsheet models (e.g. economic production).

These models are used to evaluate, for example, pasture utilisation and change in vegetation state or soil erosion risk across a paddock, as well as to evaluate the likely outcomes of management options over time. Of particular importance in the analysis of change in complex systems is the state-and-transition modelling framework described below.

Landassess DSS adapts the ecological concept of a state-and-transition model [Westoby *et al.*, 1989] to represent change in system state and to synthesise ecological and grazing management knowledge. A state-and-transition model comprises:

- a number of alternate "stable" system states; and
- a suite of possible transitions associated with change from one state to another.

Five state-and-transition models were identified for the prototype Landassess DSS case study region near Katherine, N.T. each representing a "pasture system" (i.e., a vegetation community-soil-land type combinations) recognised in the region [Bellamy and Brown, 1994; Ash *et al.*, 1994; Bellamy *et al.*, 1996]. States are defined in terms of the dominant composition of the ground layer vegetation. A transition from one state to another state is defined in terms of the suite of alternate causes that would lead to a change of vegetation state. Each cause in turn is defined in terms of:

- the probability that a change of state would occur given the particular cause;
- the time frame in years over which the cause needs to be maintained for a change in state to occur; and
- an indication of the confidence scientific experts have in that rule.

This implementation within Landassess DSS of the concept of a state-and-transition model allows for the recognition of the uncertainty associated with the rules for change in system state. An example of a state-and-transition model framework and a set of rules for a one transition is provided in Figure 2.

An important principle underlying this implementation of the state-and-transition model is that the transition rules for a change in system state (e.g., from State A to State B) can be very different from those to reverse that change (e.g., from State B back to State A). Moreover, each system state has multiple potential pathways of change depending on combinations of climatic circumstances and/or management practices. The state-and-transition model does not model the whole ecological system, rather it models the critical change processes (i.e. it provides a representation of the driving factors or major constraints to change of the interaction of the pasture ecological system and human management intervention). The state-and-transition model framework thus accommodates non-linear systems behaviour and discontinuous change in rangeland systems.

3.2.4 The Knowledge Base

Much of the knowledge required for Landassess DSS was not embodied in any formal scientific model which could easily be incorporated into a DSS. KBS (which includes expert systems and rule-based systems) allows for the representation of expert and anecdotal knowledge which may be qualitative and uncertain in nature. The knowledge

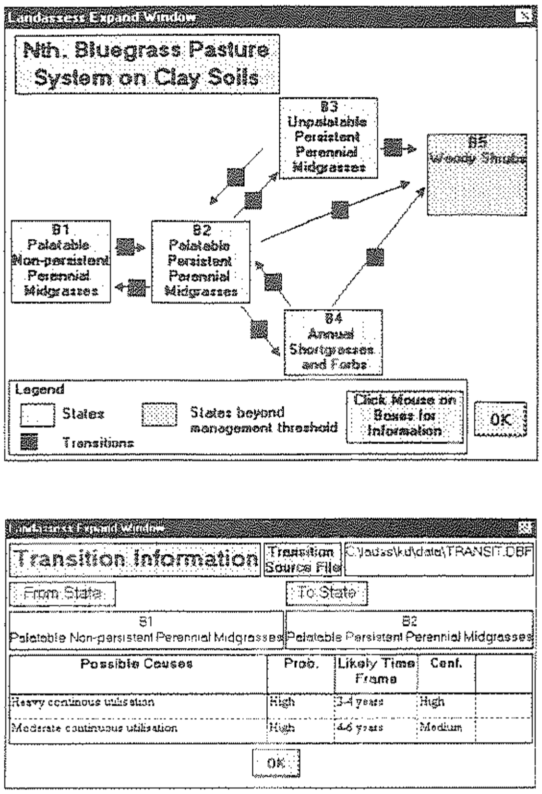

Figure 2: Example of a state and transition model framework and transition rules from state B1 to state B2.

may be represented in a number of forms, including IF..THEN.. rules, which allow for inferences to be made. The KBS of Landassess DSS incorporates expert and anecdotal knowledge about vegetation states, transitions between states, soil erosion risk, and management information [Bellamy *et al.*, 1996; Lowes and Bellamy, 1994]. Its functions include:

- defining a number of models which are used to evaluate the likely outcomes of scenarios (e.g. state-and-transition, soil erosion risk, animal grazing preferences models); and
- facilitating linkages between different components of the DSS system (e.g. linking the knowledge base information with the various models).

Linkages between the various modules of Landassess DSS are organised through the DSS Shell (Figure 1). Of particular interest is the knowledge base-database interface. It is used in the management of the state-and-transition knowledge base and the selection of appropriate model parameters from model parameter databases. The relational database is used to hold parameters and model results in Landassess DSS. For example, the parameters for each of the pasture and animal production models are held in a relational database. The outputs from the water balance models are also held in database tables for use by the other modules in Landassess DSS.

Some of the knowledge base rules define when specific regression models and other model results are required, and thus provide an interface between the knowledge rules and the model data base in the DSS. For example, the DSS is programmed so that the rule base selects which pasture production model is most appropriate for different vegetation states, and different land types.

3.3 Scenario Analysis and Assessing Tradeoffs

The 'what if' module of Landassess DSS allows testing of hypotheses about the effects of management on vegetation and soil resources within a spatially variable paddock. As such, it models the essential elements for the user to evaluate the trade-offs between resource sustainability and economic production. The user can formulate alternative management scenarios for a paddock over specified timeframes and then compare the outcomes of the "before" and "after" situation in terms of the spatial variation in vegetation state and soil erosion risk and the implications for profitability of production.

A rangeland paddock is typically thousands of hectares in size, and generally comprises a mosaic of different land types. In Landassess DSS, each specific spatial occurrence of a land type is called a unique mapping area (UMA). The UMA is the basic spatial unit of analysis for assessing change in state in Landassess DSS. The risk of change in vegetation state is defined through knowledge-based state-and-transition models and assessed for each UMA. The major causes of vegetation change in rangelands are utilisation rate, fire regime, and the timeframe involved. Utilisation rate is determined for each UMA from the outcome of the interaction of characteristics of the current system state (i.e., palatability to grazing stock and pasture yield), stocking rate and proximity to water. Only those UMAs with a vegetation state that is rated palatable to stock are included in the assessment of pasture utilisation.

Historical climate records are used in simple water balance models to generate "green days" or "green seasons" to estimate pasture production [McCown *et al.*, 1981] for each UMA depending on its state for a range of probability levels. These in turn are used in conjunction with specified management scenarios and simple regression models to estimate animal and pasture production risks. The economic component of Landassess was developed primarily to provide a dollar value to changes in vegetation state through the corresponding changes in animal production (as measured in terms of liveweight gain). A property level trading steer model was simplified to allow evaluation for a single paddock for this purpose. This is a gross margin model which takes account of variable costs and prices and assumes that any production gain is either sold at the market price or transferred within the property when target weight is reached [Bellamy *et al.*, 1996].

To facilitate the assessment of a range of trade-offs for a given user-defined management scenario (e.g. stocking rate, fire regime, distance to water, time frame), the user is able to view the spatial variability of the most likely changes within a paddock of both vegetation state or soil erosion risk. That is, the user can compare the "before" and "after" situations. The consequent annual aggregate effect upon pasture production, animal production, and gross margins are then estimated at the whole paddock level. This allows the assessment of the likely environmental and economic trade offs. The steps in this process are shown in Figure 3.

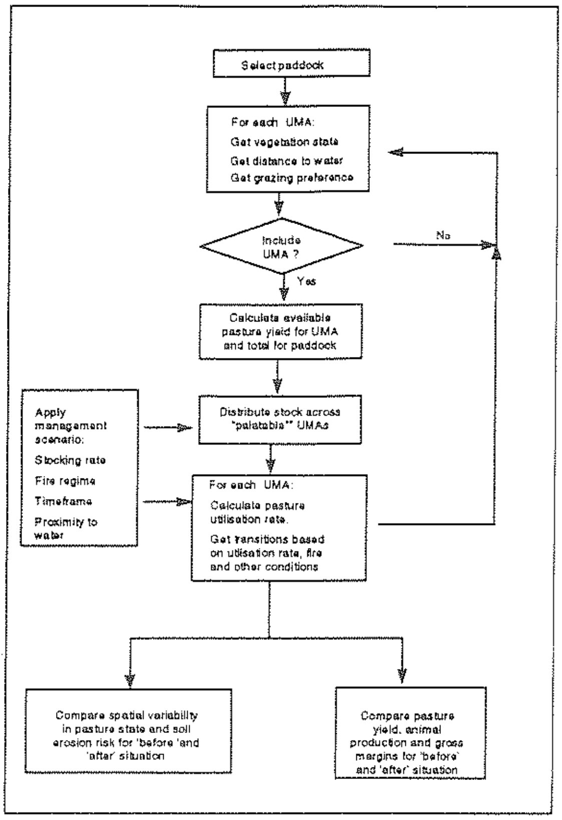

Figure 3: Flow diagram for assessing trade-offs in Landassess DSS.

4. IMPLICATIONS OF THE APPROACH

4.1 Knowledge-based Approaches

In developing a DSS, such as Landassess DSS, there is a need to make use of diverse sources and types of data and knowledge. As is the common situation in rangelands, there are numerical models and validated research available for only limited geographical areas. Much of the knowledge required in Landassess DSS was necessarily qualitative and based upon expert and anecdotal knowledge and defined for limited regions with a requirement for extrapolation. This made the use of a knowledge-based approach appropriate.

While this approach proved to be very powerful for handling much of the knowledge base available for the development of Landassess DSS, it had certain limitations relating to the effective handling of some process and temporal aspects. Some examples of limitations within the Landassess DSS system include the chaining of transitions through time, and modelling liveweight gain and pasture yield within and between seasons. Modelling in Landassess DSS was aimed at evaluating the annual aggregate effect at a management unit level.

The models that were available and the level of knowledge about the longer term processes would not have permitted development of a DSS such as Landassess DSS without the incorporation of a significant knowledge-based component. In particular, the knowledge-based approach has advantages for utilising much of the incomplete and qualitative knowledge which was available for the development of Landassess DSS.

4.2 State-and-transition Model Framework

The process of state-and-transition model development was found to provide a useful tool for increasing understanding of the dynamics of a rangeland system, and a practical framework for [Bellamy and Brown, 1994]:

- identifying the complement of potential states for a particular ecosystem;
- abstracting a complex and variable system through focusing on the key processes, and driving mechanisms of that system;
- capturing and integrating "expert" and "anecdotal" knowledge about that system;
- identifying early warning signs of potential undesirable change(s) in that system;
- identifying management "windows of opportunity" or of hazard, i.e. critical times for intervention; and
- highlighting gaps in the current knowledge base to provide a basis for prioritising future research needs.

Moreover, incorporating a state-and-transition modelling framework within a spatial DSS approach provides a powerful framework for assessing:

- current state or "health" of the system, including its dependent variables of pasture and animal production;
- potential for change in system state due to management and/or climatic circumstance;
- early warning signs of pressure or adverse management impacts on the resource base; and
- management options in terms of risks of change in system state and soil erosion risk.

4.3 Validation of Models

The approach to development of Landassess DSS and the complexities of the issues and interactions involved have significant implications for the validation of the component models and the DSS system as a whole In fact, there are theoretical reasons why it is almost impossible to fully verify or validate models of natural systems [Oreskes *et al.*, 1994]. The approach to the partial validation or confirmation of the modelling components of Landassess DSS are briefly discussed below.

Analytical validation requires checking the coherence and stability of each individual model in the DSS [Finlay and Wilson, 1991]. This was complicated for Landassess DSS due to the variation in the number of types and sources of models. The individual models have been tested to different degrees. For example, qualitative knowledge-based systems, particularly those involving relatively long time-frames, such as the state-and-transition model, are impossible to completely validate. Even when individual models have been confirmed by empirical data, their use in Landassess DSS may or may not be valid depending on the quality and quantity of input data. Moreover, the integration of a range of different models within the DSS, involving complex interactions between models across broad spatial and temporal scales, makes strict validation of the whole system problematic, if not impossible.

Synoptic validation involves checking that an acceptable output is achieved for each set of inputs, which contributes to the overall validation of the entire system [Finlay and Wilson, 1991]. During the development of Landassess DSS and its knowledge bases and models, iterative testing of the outputs from the models occurred through workshops and demonstrations with local and scientific 'experts'. The feedback from these interactions was then incorporated into the DSS. User confirmation in general was an important part of the DSS development process. However the performance of the integrated system was not validated in the strict sense. Landassess DSS was developed primarily to raise discussions about grazing management options and to challenge existing assumptions; not to set down a set of prescriptive rules. In this regard, the prototyping iterations demonstrated synoptic validation in that Landassess DSS consistently generated meaningful discussions about grazing management practices and the concept of sustainability amongst users.

5. CONCLUSIONS

Meeting the challenge of sustainable development requires substantial advances in our understanding of the interaction of natural and human systems. There is a basic need for modelling tools to focus the discussion, facilitate learning about the concept of sustainability, and support better understanding of the problem context in which potential changes in system state may be recognised and managed. However, there are a number of fundamental constraints to modelling change in complex non-linear systems that need to be overcome. These constraints relate to diverse issues such as: scaling mismatches, integration of non-homogeneous information, complex system interactions, uncertainty in causality, assessment of trade-offs and difficulties of model validation.

To address these issues and to help focus the debate on the concept of sustainability in rangeland pastoral management systems, knowledge-based DSS tools are needed that meet the following criteria:

(a) provides for simplified representations of the structural attributes of ecological systems (eg. system states);
(b) incorporates an explicit representation of the most important constraints or driving factors of change in ecosystem state in response to natural events, human intervention and their interaction;
(c) synthesises the results of basic and applied research for application to natural resource management at appropriate spatial and temporal scales;
(d) provides for the spatial modelling of alternative management scenarios at spatial and temporal scales relevant to human management decision-making (eg. paddock/field, property/farm); and
(e) evaluates the outcomes of alternative management scenarios that allows for the assessment of trade-offs between resource sustainability and economic production over time.

An innovative approach that handles a number of these modelling constraints and meets these criteria has been demonstrated in this paper. That is, an integrated spatial DSS that utilises object-orientated techniques, knowledge-based systems, and a state-and-transition framework for modelling change in system state within a spatial context. This relatively pragmatic approach can be adapted to other environmental contexts where managing change in system state is of importance to the sustainable development and use of natural systems.

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