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# State and transition models for rangelands. 7. Building a state and transition model for management and research on rangelands

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**Abstract**

State and transition models have recently emerged as flexible conceptual frameworks for abstracting information concerning vegetation change in rangelands. They characterise the rangeland through both a partitioning of the system in terms of multiple steady states, and the identification of transitions between those states. This paper examines the steps and some of the issues involved in building such models for resource management and research purposes. The number and nature of states defined depends on: the specific objective of management; the way in which the rangeland functions; and the state of existing knowledge about its dynamics and structure. Each transition may be defined in terms of a suite of causes which explain the mechanisms of vegetation change involved. Each cause can then be defined in terms of a probability of occurrence, a time-frame for the cause to be maintained to effect a transition, and a confidence rating in the prediction. State and transition models should be applied at spatial and temporal scales that are relevant to the scale of disturbance as well as to the context within which management decisions are made. Identifying the appropriate variables and processes that reflect these scales is critical. Developing these models should also be an iterative process involving progressive refinements to ensure validity, accuracy and usefulness.

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## Introduction

The state and transition model of vegetation change proposed by Westoby *et al.* (1989) has recently emerged as a flexible framework for abstracting information concerning complex rangeland systems for management and research purposes (e.g. see Filet 1994). This paper discusses the nature of models in general, and state and transition models in particular, and examines the steps and some of the issues involved in constructing such models.

## Nature of models

A model is a means to an end and not an end in itself. A good model is one that abstracts from all the details the significant aspects for the purpose of solving the problem at hand. Lee (1973) has described a model as:

> "... a simplified statement of what seem to be the most important characteristics of a real-world situation; it is an abstraction from reality which is used to gain conceptual clarity — to reduce the variety and complexity of the real world to a level we can understand and clearly specify."

Models are used for many purposes including:

(1) vehicles for communication of ideas, concepts, and theories (such as to the broader community);
(2) frameworks to describe and/or explain the behavior of systems over time (e.g. to uncover dynamics of natural systems as a means of developing theories of vegetation change, and making the theory operational so that it can be refined and tested);
(3) predictive tools to allow evaluation of the conseqences of past, present and future events or situations for planning or management purposes at a range of managerial levels (e.g. policy making, enterprise); and

(4) frameworks for identifying gaps in knowledge, and setting research priorities.

Potential uses of models in the management of rangelands are in understanding the behavior of such systems (i.e. system description) and in analysing the outcomes of management options (i.e. system forecasting or prediction).

There are many different approaches to modelling (e.g. Carlson *et al.* 1993). In the context of modelling vegetation change, a useful framework is provided by the 3 types of models of reality distinguished by Nyerges (1991) — descriptive, explanatory, and predictive. Nyerges (1991) considered that all models are based on some form of description, and that each type of model can be embedded within the succeeding type. Thus, a descriptive component can be embedded in an explanatory model and an explanatory component can be embedded within a predictive model. Classification, generalisation, aggregation and association can be used to structure descriptive models. Causal tendencies are the possibilities of things acting in a certain way because of inherent generating mechanisms. The identification of causal tendencies is the basis for explanation in explanatory modelling (Nyerges 1991). Predictive models incorporate some capability for analysing scenarios. For example, such models might generate some form of prediction of future states and the expected probabilities of these states occurring within the system.

## Mechanisms of vegetation change

In the last 30 years, conceptual models of vegetation change have shifted from deterministic, single-path successions to a focus on mechanisms of change (Pickett *et al.* 1993). Some examples of mechanisms of vegetation change which may produce alternative persisting states relevant to grazing management have been summarised by George *et al.* (1992) as:

(1) demographic inertia — some plant populations require a rare event for establishment but the resulting cohort can persist for relatively long time periods.
(2) seed-bank and germination — each patch in a grassland is in a state of almost constant change with conditions during the time of germination and establishment determining the species composition. The key factors are seed-bank changes and short-term weather patterns.
(3) grazing impacts — plant abundance may vary discontinuously and irreversibly in response to changes in stocking rate.
(4) establishment and competition — differences in the timing of germination as well as early seedling vigour and development largely determine competitive ability of different species, while the initial abundance of species may influence the outcome of competition and eventual population mixes.
(5) fire feedback — some plant species are promoted by fire while others are adversely affected.
(6) irreversible changes in soil condition — some pasture systems (e.g. annual pastures) are more susceptible to erosion than others due to lack of continuous cover or the nature of the topography. In other systems, some soil types may be more susceptible to compaction by trampling or crusting. This may reduce infiltration and percolation, and lead to the concentration of roots near the surface, which may affect establishment.

These factors may operate either alone or in concert. Identification of such mechanisms is an essential basis for developing an effective explanatory component for any model of vegetation change.

## The state and transition model

The state and transition model proposed by Westoby *et al.* (1989) is essentially a conceptual framework for abstracting information concerning vegetation change that is relevant to the management of rangelands. This model assumes the existence of multiple steady states in rangelands. It does not attempt to simulate the underlying system processes, but can be used to characterise the rangeland structure and dynamics through a description of the system in terms of a catalogue of alternative vegetation states and possible transitions between states.

Westoby *et al.* (1989) envisaged a vegetation state as a relatively stable assemblage of plant species, which was the product of the interaction of a number of independent environmental factors (e.g. climate, soils) and management actions (e.g. stocking rate, burning regime). For a plant community to change from one stable state to another requires the intervention of an external factor relating to climatic circumstance, management, or both. Environmental factors vary with time, and the impact of the interaction of these factors with management actions on individual vegetation species is either an advantage or disadvantage to grazing management, depending on the nature of the changes in these environmental factors. As both pasture productivity and composition and the social, economic and political context of management are continually changing, the state and transition modelling approach emphasises timing and flexibility in management rather than the implementation of a fixed strategy. The management objective, therefore, is to recognise and take advantage of management opportunities and to avoid hazards, however infrequent and unexpected they may be.

Westoby *et al.* (1989) perceived a model as "a system of concepts, generalisations, or assumptions" that "guides what data are collected, and how that information is assembled so as to arrive at management decisions". A state and transition model provides a useful tool for increasing our understanding of the dynamics of a rangeland system, and a practical framework for:

(1) abstracting a complex and variable system through focussing on the key processes and driving mechanisms of that system;
(2) capturing and integrating "expert" or "anecdotal" knowledge about that system;
(3) identifying early warning signs of potential undesirable change(s) in that system;
(4) identifying management "windows of opportunity" or of hazard, i.e. critical times for management intervention;
(5) providing a focus for community discussion and communication; and
(6) highlighting gaps in the current knowledge base to provide a basis for prioritising future research needs.

Most applications to date of the state and transition model (e.g. Westoby *et al.* 1989; Laycock 1991; Hunt 1992) have been largely descriptive with only poorly developed explanatory components. However, when a state and transition model is embedded in a more integrated system with some spatial analysis capability, such as a spatial decision support system (e.g. Bellamy *et al.* 1993a; 1993b), this integrated spatial modelling framework has the capacity to incorporate a flexible and comprehensive explanatory component, and provide a predictive capability for evaluating outcomes of management options.

## Principles for the design of state and transition models

Model development should be an iterative process, involving progressive refinements to the model structure and content, and even the objectives of the whole exercise. The process of knowledge acquisition for the development of a state and transition model is diagrammatically shown in Figure 1. It is also described as a series of steps below. While the decision to adopt a state and transition framework for a model may be simple, the actual process of knowledge acquisition for model development is no small task, and can be very time consuming. Therefore, careful planning and defining of objectives is essential.

### *Define the objective*

A first step is to define clearly the problem to be addressed, the specific objective for the use of the model and the intended end user. Without an explicit statement of the objectives of the exercise, it will not be possible to decide on the key factors of concern or the driving mechanisms to be considered, or what level of generalisation, aggregation, or classification is acceptable. It is perfectly reasonable to have as an objective the building of a model to understand the behavior of a system (for example, to identify management opportunities), but it is important to recognise that the emphasis is on the understanding of the phenomena, and not on the model itself (Lee 1973).

The key questions here are: What is the purpose of the model and for whom is it being developed? For example, is it to conceptualise a pasture system for research workers with the objective of conserving biodiversity, or is the model being developed for better understanding of the management of the vegetation resource to ensure sustainable livestock production? The answers to these questions will determine how time is to be treated in the model, i.e. the planning horizons over which predictions are to be made, and the frequency of the management decisions.

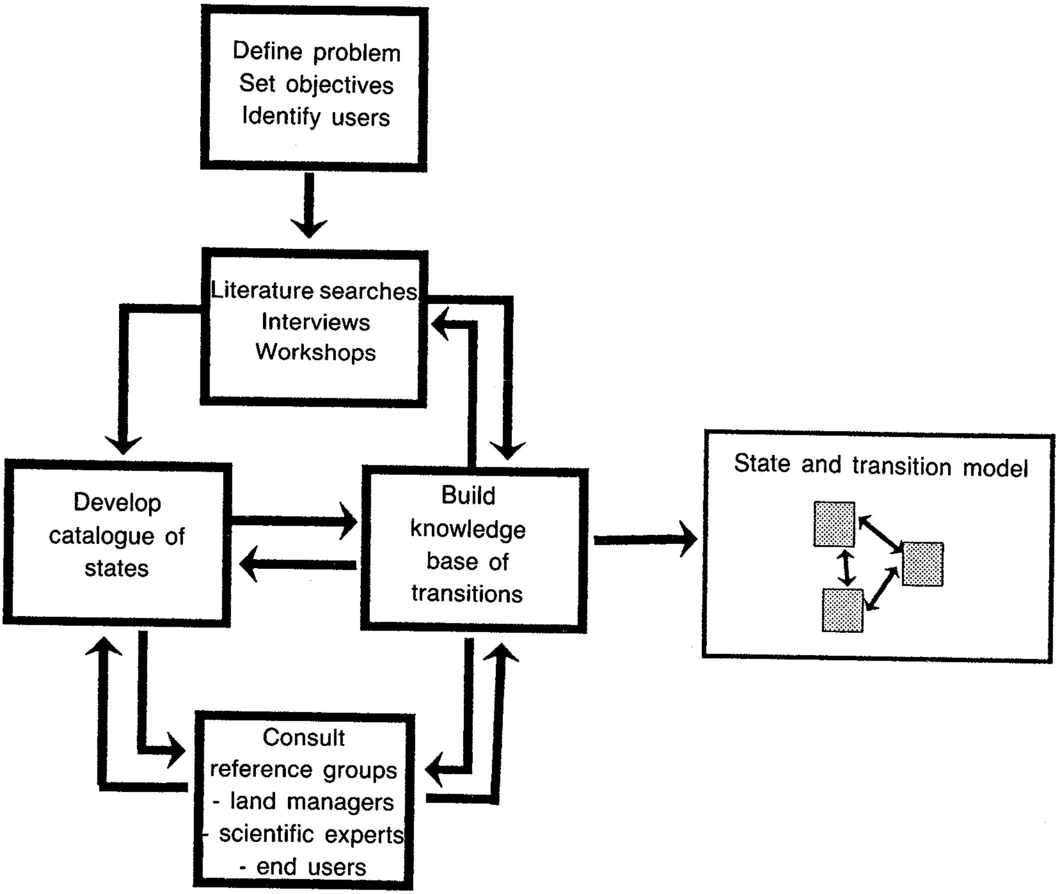


**Figure 1.** Knowledge acquisition process for a state and transition model.

*Identify the existing knowledge base*

A second step is to identify existing data sets and other relevant sources of information or knowledge. This can be achieved through literature searches, as well as the conduct of workshops or interviews with scientific and other local "experts". The availability of information and the level and type of knowledge about the system will constrain the model design.

*Define the catalogue of states*

The third step in developing a state and transition model is the definition of the catalogue of states relevant to grazing management, and the catalogue of transitions between these states. Each land type/pasture community may be partitioned into a set of alternative persisting, discrete states. Each state of that system may encompass a certain degree of variation of the dynamics of the system; for example, variations in species composition that are due to a change in season that occurs annually, or to natural fluctuations in the quality of a particular season from year to year. A state, therefore, is an abstraction of reality or, in effect, a simple model that characterises the underlying processes or functions of interest within that state of the system. The number and nature of these states will depend on several factors including:

(1) the nature and objectives of management (e.g. for grazing management, the objective may be to maximise production; for conservation management, the objective may be related to biological diversity);
(2) the way in which the rangeland system functions; and

(3) the state of existing knowledge about the system dynamics and structure.

The classification system used for defining states might be in terms of, for example, dominant species composition of the ground layer, vegetation structure, percentage ground cover, and/or basal area. It may also take into account soil surface condition. The emphasis, however, should be on management rather than theoretical criteria when deciding what states to recognise in a given model. That is, distinguish 2 states only if the difference between them represents an important change in vegetation from the point of view of management (Westoby *et al.* 1989). For example, variation due to seasonal phenology of the plants would not be subdivided into different states.

Some questions for consideration when defining states for grazing management are: Does the change in vegetation reflect different values for livestock production? Does the change reflect an important indication of possible future states, such as an initial recovery phase? Is the change undesirable for long term sustainability of pasture productivity? In each case, if the response is positive and management action is required, separate states should be distinguished.

### *Define the catalogue of transitions*

As defined by Westoby *et al.* (1989), transitions may be triggered by: natural "events" or "climatic circumstance" (e.g. drought, fire); management actions (e.g. change in stocking rate, burning, supplementation, spelling); or a combination of these. Transitions may occur quickly, as in the case of vegetation changes resulting from fires, or they may occur progressively over an extended period, as in the case of the growth of a cohort of woody plants. However, systems do not come to rest half-way through a transition. Under any given management regime, susceptibility to change from one stable persistent state to another, as well as the time-frame necessary for the given management to effect that change, will vary with a number of factors. These include: the land type (based on characteristics of soil nutrients, slope, soil water holding capacity, erodibility); the composition of the suite of plant species present; and climatic circumstance.

A transition between 2 states, therefore, may be defined in terms of a suite of causes which describe the mechanisms of vegetation change involved. Each cause in that suite can then be defined in terms of a probability of occurrence, a time-frame for the cause to be maintained to effect the transition, and a confidence rating in that prediction (Bellamy *et al.* 1993a). The probability of occurrence referred to here may take 1 of 2 forms. It may be the probability of the cause or triggering event, that effects the transition, actually occurring. Alternatively, it may be the probability of a transition occurring from State *x* to State *y*, given that the vegetation is in State *x* and the "triggering" event has occurred. It must be emphasised that, for any particular state and transition model, the approach adopted must be consistent throughout. Moreover, no matter how rare or frequent an event may be, if it is likely to effect a transition to an alternate state that has been identifed, it should be recorded as a cause for that transition and the rarity of the event occurring duly noted.

The catalogue of states for a state and transition model for the red earth environments of the monsoonal tallgrass woodlands near Katherine, N.T., is schematically shown in Figure 2. Some examples of the rule-base for transitions between 2 alternate states is also provided in Table 1. This model was developed for use in a spatial decision support system (Bellamy *et al.* 1993a; 1993b) for assessing the state of grazing lands and evaluating the outcomes of grazing management actions to the sustainability and profitability of the grazing land resource. States in this model have been defined primarily in terms of the dominant ground layer composition from the perspective of the attractiveness of forage on offer (palatable/non-palatable grasses), vegetation life form (woody/non-woody/herbaceous plants), the grazing tolerance of the species (persistent/non-persistent grasses), and the perenniality of the ground cover (perennial/annual). The key driving factors of this rangeland system identified include: utilisation rate; quality of the wet season; time of disturbance; and frequency and timing of burning.

### *Evaluate the model*

One final consideration in developing a state and transition model is determining how to assess the appropriateness of the model for its intended use. Four basic criteria against which a model can be evaluated are (Lee 1973):

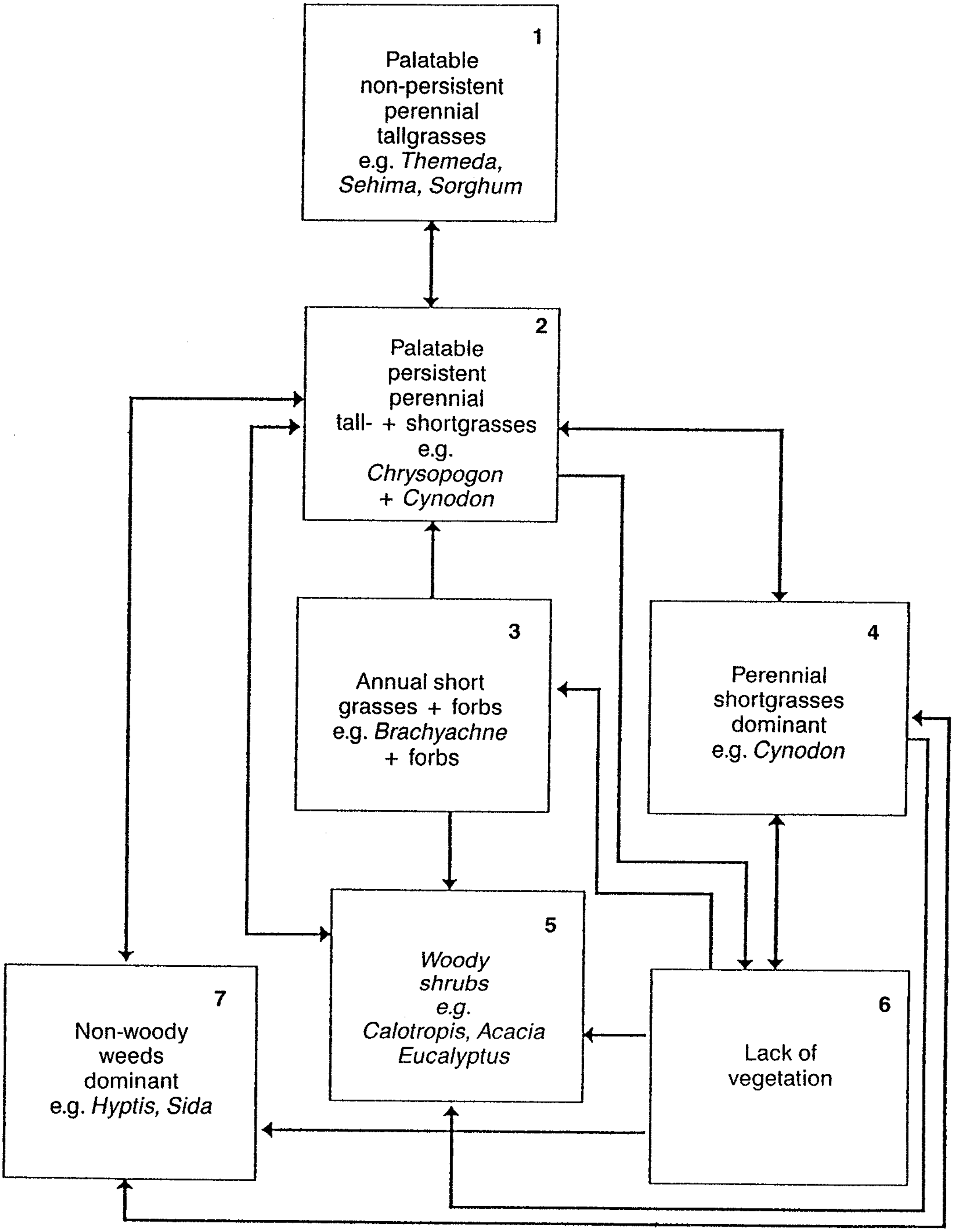


**Figure 2.** State and transition model for the red earth/*Themeda*/frontage environments, Katherine, NT.

**Table 1.** Examples of transition rules for the red earth/*Themeda*/frontage environments, monsoonal tallgrass woodlands, NT. T(x,y) means the transition *from* State x *to* State y.

| | | | |
|---|---|---|---|
| **T(1,2)** | | **T(2,1)** | |
| Cause: | Moderate early wet season utilisation (30–60% of annual herbage growth) | Cause: | Strategic burning with no or very light utilisation and seed source for *Themeda triandra* in system |
| Probability: | High | Probability: | Low-moderate |
| Time-frame: | 2–5 yr | Time-frame: | 2+ yr |
| Confidence: | High | Confidence: | Moderate |
| or | | | |
| Cause: | Continuous heavy utilisation (>60% of annual herbage growth) | | |
| Probability: | High | | |
| Time-frame: | 2–3 yr | | |
| Confidence: | Moderate | | |
| **T(2,6)** | | **T(6,4)** | |
| Cause: | Heavy utilisation (>60% of annual herbage growth) | Cause: | Seed source present for annuals, forbs and good soil surface condition |
| Probability: | High | Probability: | Moderate |
| Time-frame: | 5+ yr | Time-frame: | 2 yr |
| Confidence: | High | Confidence: | High |
| | | **T(4,2)** | |
| | | Cause: | No, low or strategic (i.e. in dry season only) utilisation (<30% of annual herbage growth) with a source of palatable persistent perennial grasses available |
| | | Probability: | Low |
| | | Time-frame: | 4+ yr |
| | | Confidence: | Moderate |

(1) Accuracy — The accuracy of a model is dependent upon the ability to perceive the "real-world" system clearly. Certain critical aspects of a model's behavior can be compared with the behavior of a real-world system. A model may also be conceptually correct but lack the ability to predict with acceptable degrees of accuracy (Loewer 1989).

(2) Validity — The validity of the model's structure in respect of its relationships between variables is as important as the accuracy of the model in terms of system behavior.

(3) Constancy — This is of critical importance if the model incorporates a predictive component. It is concerned with the extent to which the relationships which exist at present can be expected to remain constant over time.

(4) Availability of estimates of variables — Whether or not a model can be used successfully for prediction depends on the availability of estimates of future values of the key variables. It is, therefore, essential to consider carefully the selection of variables included in the model in terms of the ease and accuracy with which they can be measured or forecast.

Evaluation of the model should be an on-going iterative process during the course of model development, with frequent checks made on the model validity, accuracy and usefulness (Figure 1). Scope exists for misspecification and other errors when developing a knowledge base (e.g. for definition of transitions between states), and it is essential that the reliability of the model outcomes are checked during the course of its development. However, because of the complex and uncertain nature of natural systems and the lack of "perfect" information, model validation is extremely difficult. Confidence in a model can be built up by continuous review over time as the model evolves, as well as through the incorporation of some measure of uncertainty of the model prediction (e.g. an explicit statement of confidence in the rules for transitions).

A principal concern should be with measuring the ability of the model to replicate the performance of its real-world counterpart within acceptable limits. This may be achieved through the subjective evaluation of the reasonableness of the model output by a domain expert, and the judgement of the market-place (e.g. research peers, land managers, and other stakeholders) (Harrison 1991).

## Scale factors

One major difficulty facing land managers is the spatial and temporal heterogeneity of rangelands in northern Australia. No 2 management units (i.e. paddocks, properties) are the same. A major driving force of vegetation change across a landscape is the interaction of the variability in rainfall with the variability of the natural resource base. Both of these factors may vary spatially and temporally.

In grazing management, the concern is with the quantity, quality and timing of forage produced. The grazing resource, however, may appear heterogeneous at one spatial scale but relatively homogeneous at another. Models of change in productive potential of grazing lands are, therefore, scale dependent. They also need to operate at time scales compatible with grazing management issues. For example, as vegetation cover varies between seasons (i.e. wet and dry), the assessment of vegetation cover will depend on both the timing and the time frame over which the assessment takes place. Models of vegetation change for grazing management, such as state and transition models, therefore, need to be applied at spatial and temporal scales that reflect not only the scale of disturbance, but also the scale of assessment. They need to reflect the interaction between how animals utilise a landscape and how external factors (e.g. fire, drought) impact on the natural resource base. They also, however, need to reflect the spatial and temporal context in which management decisions are made.

State and transition models have been considered to be applicable only to "event-driven" rangelands, such as arid and semi-arid rangelands (e.g. Mentis *et al.* 1989). However, the validity of this assertion depends on how "an event" is defined, i.e. its spatial and temporal context. For example, an event may be a single localised storm, a wet season, or a production cycle.

Ultimately, scaling considerations for model development are dependent on the basic questions being asked. Natural systems, foraging animals, and human management decisions all operate at different spatial and temporal scales (Bellamy *et al.* 1993). Processes and parameters at one scale may not be important or predictive at another across the landscape (Turner 1989). As Weins (1989) points out, the "dynamics within a domain are not closed to the influence of factors at finer or broader domains, they are just different". Identifying the appropriate parameters and processes at the particular scale of relevance to the problem at hand, therefore, is a critical factor in the successful application of state and transition models to grazing management issues.

## Conclusion

The power of a model for describing vegetation change can be judged on its ability to link concepts of vegetation change to observed reality. The application of a model to a real-world problem, however, is not a simple process. Essential ingredients of success are that the approach to state and transition model development involves: firstly, a clear identification of the real purpose of the model; secondly, an iterative process of development with progressive refinements to and evaluation of the model structure and content; and thirdly, the participation of as many relevant "experts" as possible in this process.

## References

Bellamy, J.A., Lowes, D. and MacLeod, N.D. (1993a) A decision support system for the sustainable use of Australian monsoonal tallgrass woodlands. *Proceedings of the XVII International Grassland Congress, Palmerston North, New Zealand*, 1993. 3, 1929–1930.

Bellamy, J.A., Lowes, D. and MacLeod, I.M. (1993b) A spatial decision support system for assessing the state of grazing lands. *Proceedings of the Northern Australian Remote Sensing and GIS Forum 1993, 9-11 August 1993, Darwin, NT* pp. 267-276. (University of NT: Darwin).

CARLSON, D.H., THUROW, T.L. and JONES, C.A. (1993) Biophysical simulation models as a foundation of decision support systems. In: Stuth, J.W. and Lyons, B.G. (eds) *Decision Support Systems for the Management of Grazing Lands. Man and the Biosphere Series, Vol. II*, pp. 37-67. (UNESCO: Paris).

FILET, P.G. (1994) State and transition models for rangelands. 3. The impact of the state and transition model on grazing lands research, management and extension: A review. *Tropical Grasslands,* **28**, 214-222.

GEORGE, M.R., BROWN, J.R. and CLAWSON, W.J. (1992) Application of nonequilibrium ecology to management of Mediterranean grasslands. *Journal of Range Management*, 45, 436-440.

HARRISON, S.R. (1991) Validation of agricultural expert systems. *Agricultural Systems*, **35**, 265-285.

HUNT, L.P. (1992) Piospheres and the state and transition model of vegetation change in chenopod shrublands. *Australian Rangeland Society 7th Biennial Conference, 5-8 October 1992, Cobar NSW*. pp. 37-45.

LAYCOCK, W.A. (1991) Stable states and thresholds of range condition on Northern American rangelands: A viewpoint. *Journal of Range Management*, **44** (5), 427-433.

LEE, C. (1973) *Models in Planning*. (Pergamon Press: Oxford).

LOEWER, O.J. (1989) Issues on modelling grazing systems. In: Marten, G.C. (ed.) *Grazing Research: Design, Methodology, and Analysis*. CSSA Publication No. 16. pp. 127-136. (Crop Science Society of America and American Society of Agronomy: Maddison, USA).

MENTIS, M.T., GROSSMAN, D., HARDY, M.B., O'CONNOR, T.G. and O'REAGAIN, P.J. (1989) Paradigm shifts in South African range science, management and administration. *South African Journal of Science*, **85**, 684-687.

NYERGES, T.L. (1991) Geographic information abstractions: conceptual clarity for geographic modelling. *Environment and Planning A*, **23**, 1483-1499.

PICKETT, S.A., COLLINS, S. and ARMESTO, J. (1993) Models, mechanisms and pathways of succession. *The Botanical Review*, **53**, 335-371.

TURNER, M.G. (1989) Landscape ecology: the effects of pattern on process. *Annual Review of Ecological Systems*, **20**, 171-199.

WEINS, J.A. (1989) Spatial scaling in ecology. *Functional Ecology*, **3**, 385-397.

WESTOBY, M., WALKER, B. and NOY-MEIR, I. (1989) Opportunistic management for rangelands not at equilibrium. *Journal of Range Management*, **42**, 266-274.