State and transition models for rangelands. 3. The impact of the state and transition model on grazing lands research, management and extension: A review

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Abstract

The ability of the state and transition (S&T) model to improve the understanding of vegetation change in grazing lands is reviewed. The S&T model has been used as an additional research tool to collate previous knowledge into an improved format, to focus new research into key areas and to provide an improved perspective for ecological principles. By identifying the different states in a grazed vegetation and factors that cause transition between states, the understanding of vegetation change is enhanced and a framework is established in which relevant management manipulations can be planned. Recognition of the strengths and limitations of the S&T model is required if benefit to grazing land management is to occur.

Introduction

Maintaining or improving the grazing resources of northern Australia is a common goal of both land managers and research and development agencies. Research outcomes need to be coordinated into practical options which can be adopted by the grazing industry. A common approach is needed to understand and manage the grazing resource.

Westoby *et al.* (1989a; 1989b) presented a structure for organising information on vegetation change, which is also applicable for data collection and research purposes. This structure, called the state and transition (S&T) model, has evolved from previous tenets on vegetation dynamics presented by various authors (e.g. Westoby 1980; Noy-Meir and Walker 1986; Walker 1988) and is presented as a conceptual model for rangeland ecology (Walker 1993). The S&T model is a descriptive catalogue of vegetation states and transitions between the states. It provides the options of a conceptual or qualitative model and a quantitative compilation (of data) that details the rate or probability of a transition. The options can be combined or used separately.

In this review, applications of the S&T model are examined. Conceptual developments in ecology and the application of an S&T framework for grazing land management are also considered. The term "S&T framework" is used in preference to "S&T model" in keeping with the intent of the authors who state: *"We are proposing the state and transition formulation because it is a practicable way to organise information for management, not because it follows from theoretical models about dynamics"*. If the S&T framework can improve the understanding of vegetation change in grazing lands, then it will provide some further impetus on how grazing and land managers can maintain or improve the grazing resource of northern Australia.

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Basic ecological concepts

The synthesis of studies on vegetation dynamics provides the basis from which general ecological principles are formed. The application and extrapolation of these principles for either further understanding or for management of vegetation is not always successful, and refinement is required. On the other hand, where knowledge and management benefit from the useful application of a principle, wide use will be made of that principle. The value of the S&T framework needs to be considered in this perspective, particularly as successional theory has long been a basis on which to understand vegetation change (Whalley 1994). However, the value and applicability of the succession theory for grazing land management have been challenged (e.g. Mentis *et al.* 1989; Svejcar and Brown 1991; Danckwerts *et al.* 1993; Joyce 1993).

Evidence that vegetation can exist as one of a number of steady states (Dublin *et al.* 1990; Laycock 1991) is what contrasts the view of multiple steady states with the continuum conditions of the successional perspective (Clements 1916). Separating each of the steady states is a threshold, which Friedel (1991) suggests has features similar to those presented in the S&T framework, namely: a boundary in space and time between 2 states; and the transition across that boundary is not reversible on a practical time scale without substantial intervention. Laycock (1991) argues that the concept of thresholds will help clarify vegetation change regardless of whether a system is described in terms of state, domain, basin of attraction, stability, successional trajectory or suspended stage of succession.

The relative magnitude of a threshold is conceptually well described by the analogy of a "ball and trough" (Laycock 1991; George *et al.* 1992). The depth of a trough represents the strength of the local stability or the energy or strength of disturbance required to force the community across a threshold and into another state. In the S&T framework, such a representation of thresholds describes transitions in terms of probability of occurrence. When described in terms of opportunities and hazards, a measure of some form helps management appreciate the magnitude of a transition opportunity.

The S&T framework has been employed to explain the existence of a threshold between a woodland and a grassland (Burrows 1990, 1991; Whalley 1992). Certain combinations of trees and grass only represent a transient state, from which transitions across a threshold result in either a woodland or a grassland. A critical loss in soil is also considered to result in an irreversible transition across a threshold (Friedel 1991). However, the inclusion of soil parameters to describe various states is lacking in current S&T frameworks. Bosch and Kellner (1991) included surface erosion and soil compaction measures, albeit relative rankings, to expand a description of vegetation conditions. Whether changes in soil conditions preceded the change in vegetation or were subsequent or simultaneous to vegetation changes could not be determined by this study. This typifies a deficiency of linking soil processes with vegetation dynamics.

Applications

On the basis of the S&T framework, a number of grazed communities have been described as a catalogue of states linked by a series of transitions. As a research tool, the S&T framework to date has been used for vegetation surveys and for developing a decision support system. Also, the S&T framework has supported developments in animal production, land management, and temporal and spatial considerations.

Catalogues

The diagrammatic layout of the S&T framework, similar in style to those previously used by Gadgil and Meher-Homji (1985), Noble *et al.* (1986), Silcock *et al.* (1988) and Lodge and Whalley (1989), is a clear format by which to describe dynamics of vegetation communities. Westoby *et al.* (1989a) gave 3 initial examples: a saltbush shrubland in southern Australia; a semi-arid grassland–woodland in eastern Australia; and a tall grassveld in South Africa. Additional communities have since been described (Table 1).

The collation of portions of knowledge on the vegetation dynamics of a community, using the S&T framework, has resulted in a number of synthesis summaries (Laycock 1991; George *et al.* 1992; Hunt 1992; Huntsinger and Bartolome 1992; Whalley 1992; Hodgkinson 1993). Common to these summaries are listings of important factors that affect the dynamics of the community. For example, George *et al.* (1992) highlighted seed-bank and germination, establishment and competition, grazing impacts, fire feedback and irreversible changes in soil condition as factors affecting the dynamics of an annual-dominated grassland. Referral to the catalogue of transitions identifies when each factor is active and which states of the vegetation are affected.

The S&T framework has also provided an initial format for preliminary investigations on the vegetation dynamics of a community (De Pietri 1992; Ash *et al.* 1993; Bellamy *et al.* 1993).

Table 1. Publications utilising a state and transition diagrammatic layout.

Author	Location	Vegetation type
Ash *et. al.* (1993)	North Australia: Charters Towers; Katherine	tallgrass/monsoon grass savanna
Bosch and Kellner (1991)	South Africa	semi-arid grassland
Brown and Smith (1993)	California, USA	annual Mediterranean grassland
De Pietri (1992)	Patagonia, Argentina	forest, scrub and grassland
George *et al.* (1992)	California, USA	annual Mediterranean grassland
Hodgkinson (1993)	Lake Mere, NSW	mulga woodland
Hunt (1992)	South Australia	bladder saltbush piosphere
Huntsinger and Bartolome (1992)	California, USA; southern Spain	oak woodland
Jones (1992)	Samford, Queensland	sown setaria pasture
Laycock (1991)	Utah, USA	sagebrush-grass
Westoby *et al.* (1989a)	riverine plain, NSW and Victoria	bladder saltbush
Westoby *et al.* (1989a)	western NSW	semi-arid grassland and woodland
Westoby *et al.* (1989a)	South Africa	tall grassveld
Whalley (1992)	New England Tableland, NSW	woodland and grassland

The stable states in a community are compiled by deriving some states from field survey data, and others from considered opinion (Ash *et al.* 1993). As new field data come to hand, adjustments can be made. The inclusion of animal production data as an additional "state descriptor" (Ash *et al.* 1993) markedly increases the relevance of an S&T presentation for grazing. To date, most studies using the S&T framework have not included animal production data.

In some investigations on vegetation dynamics, the S&T framework is used as a supporting or modifying concept in the interpretation of results. For example, the dominance of *Eragrostis lehmanniana* in Southern Arizona semi-desert grasslands for over 30 years was considered by Anable *et al.* (1992) in S&T terms as a new stable state of vegetation that would resist composition changes without major anthropogenic inputs. Morris *et al.* (1992) examined species change in a South African tall grassveld and suggested that prediction of species changes could be improved with the S&T framework. As a modifying concept, the S&T framework would accommodate the recorded pathways of change in at least 2 dimensions, rather than along a single reversible gradient.

Transitions

The S&T framework can be used to explain causes of change in the composition of a pasture or vegetation type. Jones (1992) identified heavy grazing as the cause of change from a desired sown pasture to a less productive naturalised pasture by applying the concepts of S&T. He showed that, by resting, a transition back to a desired sown pasture was achieved, but the rate of recovery diminished with increasing periods of prior heavy grazing. After 10 years heavy grazing, this transition was no longer achieved. In this instance, timely spelling is critical for recovery. In an S&T framework, this last comment typifies what would be highlighted in the catalogue of transitions for this community.

The interaction between 2 factors can also influence transitions in a vegetation community. Jameson (1991) identified fluctuations between dominance by cool or warm season species in a mountain grassland in Colorado as dependent on the timing of harvesting and the intensity of harvest. The application of these results is developed in an S&T framework, whereby opportunistic management is the strategy by which change may be initiated and the probability of one transition is compared with the other.

Results from the reductionist methodologies of Jones (1992) and Jameson (1991) are well adapted to the S&T framework. A series of this type of examinations may be required to build an initial S&T framework for a vegetation community. Subsequent validation under paddock grazing, with interactive influences such as variable climate, would further improve the description and quantification of states and transitions. Hodgkinson (1993) undertook such an approach in a demographic study on perennial grass species in mulga *(Acacia aneura)* woodlands. Concerns over adverse changes in the state of vegetation as a result of unsuitable grazing pressure were confirmed from this study.

Circumstance and mechanisms involved in the change, namely feral animal and heavy stock grazing, wildfire control, shrub germination, drought and drought feeding of browse, were identified in an S&T framework.

The occurrence of transitions in a community can be infrequent and experimentally difficult to induce. However, one approach to identify a transition and compare the consequences of different transitions is by simulation. Dublin *et al.* (1990) utilised a model of tree population dynamics to determine how a woodland in Kenya changed to a grassland, given a series of feasible options. This analysis utilised the elements of the S&T framework, by assuming that the 2 vegetation communities were separate states and that change could only occur given certain conditions. By comparing the various simulations, fire alone was identified as the factor responsible for a trend towards an open grassland in the 1960s and that herbivore grazing by elephants in the 1980s prevented woodland recovery. The applicability of simulation for the analysis of state and transition models in rangeland ecology is examined by Scanlan (1994), where predictions of change are described for woody and pasture communities.

Once transitions are identified, clarification of the factors that influence the transition may still be required. Whalley (1992) categorised factors that influence transitions, as per the "state factors" of Jenny (1961), under climate, organisms, time and additional factors. These groupings provided an additional qualification of the transitions and have been used to collate knowledge of the dynamics of a woodland-grassland community in northern NSW (Whalley 1992).

Vegetation surveys and monitoring

An analysis of a vegetation survey benefits from a structured format by which to make comparisons and interpretation. Outcomes from ordination analysis can utilise the S&T framework to present a description of surveyed vegetation (Bosch and Kellner 1991; De Petri 1992). De Petri (1992) correlated past and current intensity of grazing and use of fire with composition and structure of forests in Argentina. Change agents were then used to link the various states in either an ecosystem model or a landscape model using the S&T framework. The survey by Bosch and Kellner (1991) contrasted successional pathways based on grazing pressure. However, the identification of boundaries, preventing reversible transition, between different "domains of attraction" added a non-equilibrium aspect normally absent from a successional analysis. They modified the description to an S&T model to identify which attributes are associated with which "domain of attraction".

Both of these surveys suffer from a "single point in time" comparison between sites, with the assumption that all critical influences have been catalogued. Transitions defined in this manner will generally not include major stochastic events or interacting effects. Nevertheless, once the framework is established, refinements and additions can be derived from further monitoring (Bosch and Kellner 1991).

Any framework (S&T or other), established from an initial survey, benefits subsequent monitoring. In the above 2 studies, further vegetation assessment provides an operational tool for deciding whether current management at that location should be maintained or modified. Based on the value of parameters in each state, De Petri (1992) proposed a measure of key species occurrence, cover and biomass as an indicator data set for determining the state. Bosch and Kellner (1991) utilise a species frequency and basal area measure to determine in which "domain of attraction" a site is located.

Framework to develop a decision support system

The use of the S&T framework as a template from which to develop a knowledge-based decision support system, DSS, (Bellamy and Lowes 1992; Bellamy *et al.* 1993) highlights the capacity of the S&T framework to integrate information. Sources of expertise for the knowledge base include published works, in addition to practical and non-documented experience from pastoralists and scientific experts. By utilising existing resource data, the addition of a Geographic Information System (GIS) component into this DSS will allow assessment of the spatial impact of alternative management strategies. It enhances any regional or district predictions (e.g. Agency Drought Location Maps or Seasonal Climate Forecasts), and can provide "what if" simulations for graziers if the resolution at a property level is workable. This approach is not commonly considered in other S&T applications, which is indicative of the difficulty of integrating a spatial component into ecological outcomes. Joint work or co-operation between resource specialists versed in GIS applications and field ecologists may overcome this deficiency.

Animal production

In grazing systems described by S&T frameworks, a measure of animal production for each state is generally not included; however, the paper by Ash *et al.* (1993) is an exception. Despite general consensus that animal productivity will decline if less palatable species dominate a pasture, Mentis *et al.* (1989) report evidence of poor relationships between animal production and species composition. Ash *et al.* (1993) found animals gained more weight in the short term from a pasture in poor condition than one in good condition. Clarification of the relationship between animal production and different states of pasture will improve as more studies include a measure of animal production when comparing states.

Methods to clarify the issue can benefit from the use of an optimal foraging model, which links pasture condition with animal performance (Owen-Smith 1991). Another approach to identifying differences between states is proposed by Wilson and MacLeod (1991). They propose testing the grazing capacity of pastures for departures from linearity with increasing stocking rates, or to compare pasture of the same vegetation type, but different grazing history, for similarity in optimum stocking rate.

Land management

Ecological principles influence land use policy, e.g. South Africa (Mentis *et al.* 1989), and are the foundation for monitoring systems used in evaluating land condition (Lauenroth and Laycock 1989). Current dissatisfaction with both the ecological principle and the effectiveness of policy and monitoring has resulted in alternative perspectives, a number of which use the S&T framework to improve the policy outcomes (Mentis *et al.* 1989; Svjecar and Brown 1991). For example, land management based on practices of maintaining a permanent equilibrium is not considered realistic. Instead, when viewed from an S&T framework, good land management involves continuously recognising and avoiding hazards and taking opportunities (Mentis *et al.* 1989; Whalley 1992).

A change in current thinking is required if land management is to improve. Mentis *et al.* (1989) suggest that important factors to consider are adequately addressed by the S&T framework, namely: range behaviour and dynamics are not under the supreme control of the grazier; and no simple, single model of range functioning appears to be universally applicable. The latter point indicates a need to devise criteria to decide which kind of model applies to what kind of situation.

Multiple use or overcoming conflicts in land use is an important issue in land management. The inclusion of a comprehensive set of attributes for each state in the S&T format will assist in comparisons. Pieper and Beck (1990) present ecosystem attributes (e.g. forage biomass, stocking rate, mammal density, bird density and erosion) for different successional stages in a range, which they also consider adaptable for an S&T framework. In Kenya, an understanding of contrasting states and transitions meant that crossing the threshold from grassland to woodland would entail a 40% reduction in elephant numbers. Dublin *et al.* (1990) argue such a change is inconsistent with current conservation practices. From a policy perspective, an argument to determining the best type of overseas aid (Mace 1991) also utilised the S&T framework as a basis for highlighting the need for program support for adapted extensive dryland grazing systems as opposed to intensive irrigated development.

Contrasts and implications that can arise for land management are highlighted by an example using the S&T framework to present a comparison of the *Quercus* (oak)-dominated woodlands in California and southern Spain (Huntsinger and Bartolome 1992). Similar states for the community were identified in both locations, but the transitions between the states were caused by different management practices. One transition, involving the loss of a shrub understorey, was caused in Spain by frequent human intervention through shrub removal or cultivation whereas in California, grazing or low intensity fire caused the change. The reverse transition of shrub invasion was generally slow in California, taking 10–15 years in the absence of fire or grazing, whereas in Spain, this transition was rapid, taking 2–5 years in the absence of fire and/or cultivation. A higher intensity of management in Spain than in California and the absence of fire in Spain resulted in different influences on the transitions. This example shows how recommendations on best land use may differ between locations.

Temporal and spatial considerations

The understanding of temporal and spatial factors can be improved with the use of the S&T framework. Bond and Richardson (1990) consider the temporal influence of climate change by using the S&T framework to examine the possible effects of fire, herbivore and climatic extremes on vegetation.

In terms of spatial factors, different land types, when under constant or fluctuating utilisation, can experience occasions when one or more of the land types become restricted in their use. Such "bottlenecks" will limit the distribution of populations, resulting in a need to take action, e.g. destock, so that a state is maintained and an unwanted transition avoided (Coughenour 1991). Identification of these locations and when such an event might happen is an outcome that a GIS-based predictive tool (Bellamy *et al.* 1993) may forecast.

The effects of temporal and spatial factors are closely linked, which Hunt (1992) typifies in the dynamics of a piosphere in a grazed saltbush community. An S&T framework is used to explain these effects, namely the existence of 3 states, depending on the distance from water. Differences in rainfall events provide a temporal influence which will move the piosphere out during extended dry periods and move in following wet and recovery opportunities.

Friedel (1993) and Stafford Smith and Pickup (1993) challenge the ability of the S&T framework to deal with temporal and spatial differences in a grazed landscape. Friedel (1993) considers the component states and the transitions to be scale dependent and specific to a particular hierarchical level of landscape. The disparity that can arise is that the measurement of botanical change in a grazed community may not match the processes of run-off and soil erosion that may occur at a landscape level. Implications for S&T frameworks include a need to be selective in the attributes measured and a need to recognise and acknowledge the hierarchical level at which an S&T framework is developed.

Stafford Smith and Pickup (1993) propose a multi-temporal and spatial framework, developed from the concepts of Stafford Smith (1992), to overcome what they consider is the poor spatial linkage between states of the S&T framework. This conceptual picture requires deriving a probability density function (portrayed as a frequency plot against n axis) of a site in relation to different site descriptors, e.g. cover, species density, soil type. The approach, still in its developmental phase, aims to present the complexity of a site rather than unduly simplify a site description so that all interacting factors and spatial influences can be considered.

Extension

Local pastoral knowledge is an important addition to any scientific information on the dynamics of grazed pastures. In developing the knowledge base for a monsoon tallgrass woodland, Bellamy and Lowes (1992) have used the S&T framework to collect practical experience from producers in interview and workshop activities.

A clear and understandable outline of vegetation processes will assist with the provision of management advice for producers. The schematic "Mulga Bill's Tennis Court" (Silcock *et al.* 1988) was little different in structure from an S&T framework, but during the 1970's it supported Dr Bill Burrows in explaining important concerns on the management of the mulga woodlands of western Queensland, Australia, to colleagues and graziers. Additional comments later, using the S&T framework, by Burrows (1990), stress that management influences are greatest when the environment is at its extremes, and during the intervening times, the recommendation of "take it easy" is supported by the concept of maintaining the system in its current state.

Danckwerts *et al.* (1993) suggest that the S&T framework can assist producers in setting and attaining production objectives. Key issues included an awareness of what state or states would have the greatest chance of achieving desired outcomes and an awareness of what combination of events and management is required to cause or prevent movement from one state to another. To implement such key management practices, O'Reagain and Turner (1992) propose that they be applied within an opportunistic framework, which they consider is a critical part of the S&T framework. Danckwerts *et al.* (1993) and O'Reagain and Turner (1992) both suggest the addition of an adaptive management framework (Stuart-Hill 1989), a planning process which provides objective evaluation of management action, to enhance management decisions derived from the S&T framework.

The way in which an S&T model is presented to grazing or land managers will influence how readily they understand the concept. Brown and Smith (1993) varied the format of their model, such that the boldness of lines (representing transitions) indicated the likelihood of change to new states and size of circle (representing states) represented stability. This is but one alternative; nevertheless clarity of presentation and relevance for management decisions will be necessary if acceptance of the S&T framework by grazing or land managers is to occur.

Conclusions

A rethinking of the concepts of ecological theory in vegetation has been stimulated in part, by the S&T framework. Consequently, it is not uncommon to find the current principles applicable to grazing land management under review (Svejcar and Brown 1992). Deficiencies in the long-accepted successional approach can be overcome if alternative perspectives such as thresholds, episodic events and non-reversible changes are adopted (Friedel 1991; Laycock 1991). Land management that accounts for such ecological behaviour is also deemed more effective (Mentis *et al.* 1989; Svejcar and Brown 1991).

The most frequent use of the S&T framework has been as an additional research tool, particularly in the area of grazing land management. Application of the S&T framework is an option for collating previous knowledge into an improved format, focussing new research into key areas, or providing a different perspective for ecological principles. This approach has received wide support since publication of the S&T framework in 1989 as detailed in this review. Minor comment on the S&T framework has also been made in other publications on range revegetation (Call and Rowndy 1991; Pyke and Archer 1991), economic models (Milham 1993), ecosystem processes (Grover and Musick 1990; Hunt 1990; Roshier 1990; Archer and Smeins 1991; Pamo *et al.* 1991; Tiedman *et al.* 1991; Provenza 1991; Bosch and Booysen 1992; Hik *et al.* 1992; van Duivenbooden 1993) and key species profiles (Noy-Meir 1990; O'Connor 1991). Interest appears greatest in the USA and Australia, with only minor comment from southern Africa. A frequent comment is the suitability of the S&T framework for better understanding of arid and semi-arid vegetations (e.g. Hacker *et al.* 1991; Stafford Smith and Pickup 1993).

The use of models to simplify reality may appear attractive, but Stafford Smith (1992) warns that accepting the S&T framework and attempting to fit all data to it is fraught with danger. Such advice is certainly valid if the S&T framework is to be developed into a reliable aid.

As a communication or extension tool for producers; little has been reported on the use of the S&T framework. Technical scrutiny of the approach is still underway and a wider understanding and acceptance of its relevance is required before major extension initiatives are based on the S&T framework. Given the growing interest by producers in grazing systems, the need for an objective framework in which to evaluate alternative systems is required. The S&T framework has the potential to assist producers in such evaluation as an extension tool.

Improvements to grazing land management practices do require a better understanding of vegetation change and its consequences for animal production and landscape stability. However, the benefits of such knowledge for research, development and extension operatives must flow on to grazing and land managers. The scope for the S&T framework to provide such a linkage from improved understanding through to practical grazing management does exist. Greater involvement by all participants with the S&T framework is required, and constant evaluation of its strengths and weaknesses needs to be ongoing, if benefit to grazing land management is to occur.

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