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State-and-transition modelling

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Key methods discussed in this chapter

State-and-transition modelling

Connection to other chapters

State-and-transition model development relies on a suite of related methods. Interviews and participant observation (Chapter 7) and participatory data collection (Chapter 8) are used to gather local knowledge to describe states and identify the causes of transitions among states. Participatory modelling and planning (Chapter 13) can involve local users in the construction of models and the linkage of models to adaptive management practices. Historical assessment (Chapter 25) identifies the ecological states and processes that are considered as references for ecological assessment while ecological field data collection (Chapter 6) provides data on extant vegetation, soils and animal communities comprising states. Statistical analysis (Chapter 18), including multivariate and machine-learning techniques, is used to develop and provide empirical validation of concepts for ecological states and to quantify transitions. Spatial mapping and analysis (Chapter 24) is used to map ecological states for use in management. Ecosystem service modelling (Chapter 31) can be used to identify the suite of ecosystem services provided by alternative states and collections of states in a landscape. Finally, expert modelling (Chapter 16) methods can be used to predict the probability of state transitions.

Introduction

State-and-transition models are tools to explain the causes and consequences of ecosystem change (Bestelmeyer et al. 2017). These models are used in several ways. Most commonly, state-and-transition models are heuristic tools to explain the processes involved in ecosystem change. They can link to specific management strategies that cause or prevent specific ecosystem changes. These models are also used in scenario development through simulations of the effects of external drivers (such as climate) and management actions (such as prescribed burning) on vegetation. All of these uses are aimed at guiding the management of ecosystems and natural resources.

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SUMMARY TABLE: STATE-AND-TRANSITION MODELLING	
DISCIPLINARY BACKGROUND	**KNOWLEDGE TYPE**
The methods in this chapter are derived from or have most commonly been used in: Vegetation Ecology, Rangeland Science, Social Science	*The methods in this chapter are primarily used to generate the following types of knowledge:* • Descriptive • Exploratory • Explanatory
RESEARCH APPROACH	**PURPOSE OF METHOD**
The methods in this chapter originate from or most commonly adopt the following research approaches: • Analytical/objective • Collaborative/process	*The most common purposes of using the methods in this chapter are:* • System understanding • Stakeholder engagement and co-production • Policy/decision support
TEMPORAL DIMENSION	**SYSTEMIC FEATURES AND PROCESSES**
The methods in this chapter are most commonly applied to the following temporal dimensions: • Present (typically within the last 5–10 years) • Recent past (post-1700s) • Future	*While most methods can do many things, the methods in this chapter are particularly good (i.e. go-to methods) for addressing the following:* • Regime shifts • Social learning • Evaluating policy options
SPATIAL DIMENSION	
The methods in this chapter are primarily either or both: • Non-spatial • Explicitly spatial *The methods in this chapter are most commonly applied at the following spatial scales:* • Local	

The state–transition concept was developed initially for arid rangelands as a flexible way of organising information about vegetation dynamics that draws on a wide range of concepts about ecosystem change (Westoby, Walker, and Noy-Meir 1989). State-and-transition models are generally consistent with concepts of resilience and regime shifts, acknowledging the potential for abrupt and persistent change in ecosystems (Briske et al. 2008; López et al. 2011). In state-and-transition models, ecosystems potentially exhibit multiple states, usually defined by changes in ecosystem structures and processes of interest. Distinctions among ecological states reflect differences in the ecosystem services provided, as well as the risks and opportunities for change in the provision of ecosystem services. Although state-and-transition models are sometimes linked to alternative stable-state theory (Petraitis 2013), in practice concepts for states are variable and based largely on management utility. States can be highly stable and resilient or be transient and change relatively easily and often. In most state-and-transition models, 'state' circumscribes both regimes and states within regimes, following Biggs et al. (2012). While state-and-transition models were initially conceived to link rangeland management to the emerging concepts of ecosystem non-equilibrium and catastrophic transitions (Walker and Westoby 2011), they have become widely used in many types of ecosystems (Hobbs and Suding 2009).

State-and-transition models have been developed and applied following four general approaches (see also Table 27.1).

1. **Conceptual state-and-transition models:** Most commonly, conceptual state-and-transition models (involving diagrams and text) are used by scientists to communicate the roles of drivers and feedbacks involved in state change (McGlathery et al. 2013). These models have been used in resilience assessments as part of the resilience planning process (Huber-Sannwald et al. 2012; Walker and Salt 2012). Conceptual state-and-transition models can include quantitative values and linkages of states and transitions to specific management recommendations (USDA 2019). Conceptual state-and-transition models with quantitative state criteria are being produced as part of government land management programmes in the USA, Mongolia and Argentina (Bestelmeyer et al. 2017).
2. **State-and-transition simulation models:** Conceptual models can be extended to simulation models. Simulation state-and-transition models use multi-temporal data (or best guesses) to estimate transition probabilities for broad land-cover states or plant communities and develop scenarios of ecosystem change under different management regimes (Zweig and Kitchens 2009; Bino et al. 2015; Perry et al. 2015; Daniel et al. 2016). Simulation state-and-transition models may be non-spatial or spatially explicit.
3. **'Process-based' state-and-transition models:** 'Process-based' state-and-transition models (closely related to simulation state-and-transition models) seek to quantify in greater detail how interacting factors influence transition probabilities (Bashari, Smith, and Bosch 2009).
4. **Ecosystem service-based state-and-transition models:** Conceptual state-and-transition models have been expanded to include information about the ecosystem services and economic values provided by states (Ritten et al. 2018).

In addition to these well-developed roles for state-and-transition models, there have been efforts towards social-ecological state-and-transition models (or regime shift models), in which feedbacks between social and ecological systems are used to define states or regimes (Easdale and López 2016; Wilcox et al. 2018).

State-and-transition models of all types are ideally co-developed by land managers and scientists for use in local decision-making (Kachergis et al. 2013). They are tools for enhancing the functioning of SES rather than for studying them (i.e. scientists as part of the SES rather than on the outside looking in). Collaboratively developed state-and-transition models have numerous benefits, including increased trust in and use of science in management, improved communication among participants from different organisations, and decreased conflict (Johanson and Fernández-Giménez 2015).

SES problems and questions

In the context of SES, state-and-transition models foster a community-level understanding of how ecosystems function and respond to management actions, particularly when there is a lack of understanding or disagreement about why ecosystems change. Community-level understanding of ecosystem function underpins collaborative efforts to promote the sustainable provision of desired ecosystem services tailored to specific parts of a land- or seascape. Several specific problems are addressed by state-and-transition models (Yates and Hobbs 1997; Bestelmeyer et al. 2010; Karl, Herrick, and Browning 2012; Kachergis et al. 2013). First, they are used to stratify the landscape according to variations in ecological potential (the plant communities which a site can possibly support) and to identify management and restoration targets (e.g. deciding what plant communities to try to restore at a particular site). Second, they are used to assess the risk of degradation and identify proactive measures to avoid it. These measures could include early-warning indicators used in grazing management or strategies for managing fire frequency in a landscape. Third, they specify constraints to, and opportunities for, desirable transitions based on a knowledge of ecological processes. The success of seeding to restore desired plants, for example, may depend on factors such as soil type, climate or rates of soil erosion. Fourth, state-and-transition models can link to specific intervention strategies that promote desirable transitions, such as a specific seed mixture that is suitable for a site. Finally, these models are used in the design and interpretation of monitoring programmes used to evaluate the success of management by specifying, for example, the plant community benchmarks against which monitoring data are evaluated.

Brief description of key methods

State-and-transition models have been co-developed by scientists, land managers and resource users in many settings (Chambers et al. 2014; Bruegger et al. 2016; Tarrasón et al. 2016). These models may or may not be used directly in resource management decisions, but reflect and influence the mental models underlying those decisions.

Best practices in developing all state-and-transition models include three steps:

1. **Define the spatial extent:** State-and-transition models should be grounded to specific land areas, which helps to avoid confusing inherent differences in ecological potential with state transitions by focusing users' attention on usefully comparable land areas. Soil, landform, and ecoregional land classifications and maps can be used to organise multiple state-and-transition models pertaining to distinct land areas. Recent advances in machine-learning-assisted digital mapping can utilise widely available global spatial datasets to create these maps. Land classifications should reflect how local people and resource users classify and distinguish land types (Bestelmeyer et al. 2009; Duniway, Bestelmeyer, and Tugel 2010; Spiegal, Bartolome, and White 2016; Maynard et al. 2019).
2. **Conceptual state-and-transition model development:** Literature review, historical records and concepts developed from semi-structured interviews of key informants are used to develop initial models for spatial areas. Ideally, workshops with collaborators are

used to introduce state-and-transition modelling concepts and refine state-and-transition models based on local and expert knowledge, using a combination of break-out and large-group discussions. Group field visits to discuss states and transitions are invaluable. Key uncertainties for testing are identified at the end of the initial workshop(s) (Knapp, Fernández-Giménez, and Kachergis 2010; Knapp et al. 2011; Kachergis et al. 2013).

3. **Model testing and refinement:** Draft state-and-transition models are used as a basis for hypothesis testing and evaluation by users. Vegetation and soil (inventory) data collected by scientists can be used to quantify state characteristics and test for differences

Table 27.1 Summary of key applications of state-and-transition modelling

Main applications	*Description*	*References*
Conceptual state-and-transition models	Conceptual or descriptive state-and-transition models are produced in a variety of ways, but involve narratives and graphical descriptions of states and transitions between states. These transitions typically involve natural drivers, management actions and feedback processes. Descriptions of states and transitions can also include quantitative values.	*Key introductory texts* Bestelmeyer et al. 2010; Bruegger et al. 2016 *Applications to SES* Barrio et al. 2018; Peinetti et al. 2019
State-and-transition simulation models – non-spatial	Conceptual models are extended to quantitative models by (a) defining discrete states (e.g. by using multivariate analysis of community data), (b) defining transitions (e.g. by using multi-temporal data, stratified sampling in space with space-for-time substitution assumptions, expert estimates), and (c) simulating scenarios of change (e.g. using transition matrix models and Monte Carlo methods featuring probabilistic or deterministic transitions between states).	*Key introductory text* Daniel et al. 2016 *Applications to SES* Zweig and Kitchens 2009; Bino et al. 2015
State-and-transition simulation models – spatial	These models are similar to non-spatial state-and-transition simulation models, but run for multiple spatial cells that can incorporate spatial variation in conditional transition probabilities and spatial processes such as dispersal.	*Key introductory text* Daniel et al. 2016 *Applications to SES* Perry et al. 2015; Miller et al. 2017
Process-based state-and-transition models	Processes involved in transitions are quantified to produce a probabilistic model of cause and effect that can be updated over time with new knowledge (a Bayesian network; see also Chapter 16: Expert modelling). Probabilistic transition estimates include uncertainty about transitions.	*Key introductory text* Bashari, Smith, and Bosch 2009 *Applications to SES* Rumpff et al. 2011
Ecosystem service-based state-and-transition models	Once conceptual or simulation-based state-and-transition models are sufficiently developed, additional information about states and transitions can be presented. This includes the multiple ecosystem services and economic values provided by states and model-based 'value-added' information on processes of interest in states (e.g. wind erosion). This is an active area of research.	*Key introductory text* Brown and MacLeod 2011 *Applications to SES* Webb, Herrick, and Duniway 2014; Eastburn et al. 2017; Ritten et al. 2018

> between alternative states. Field data are combined with local knowledge or spatial data on past management treatments to test ideas about deterministic transitions. Experimental monitoring can also provide tests of transitions over longer time frames. Workshops are used to discuss evidence and revise models iteratively. This step is, ideally, never fully completed, as collaborative groups constantly refine state-and-transition models based on new knowledge (Young et al. 2014; Bruegger et al. 2016; Porensky et al. 2016; Arterburn et al. 2018; Jamiyansharav et al. 2018; Tipton et al. 2018).

Conceptual state-and-transition model development and dissemination can be supported by systematic formats that enable state-and-transition models to be included in a database and linked to other computational tools. The ecosystem dynamics interpretive tool (EDIT) (edit.jornada.nmsu.edu) is a database for housing state-and-transition models linked to land classifications and spatial data and making these models available via the web and mobile devices. Application programming interfaces (APIs) allow state-and-transition model data to be linked to a variety of web and mobile applications. A globally accessible version of EDIT (editglobal.org) is in development.

Table 27.1 categorises and summarises the general types of state-and-transition models that have been produced and gives introductory references on state-and-transition model development methods and example applications.

Case study 27.1: State-and-transition models for management of Mongolian rangelands

The country of Mongolia has developed a system of conceptual rangeland state-and-transition models with quantification of key state characteristics (Figure 27.1). These state-and-transition models are coupled with monitoring and community-based rangeland management across the country. Communal, rangeland-based livestock production is a dominant land use, an important source of livelihood across Mongolia, and an equally important element of national identity. Rangeland management, however, changed dramatically with the transition from socialism to a free-market economy in the early 1990s. Privatisation of livestock coupled with a collapse of government support and an influx of new herders has led to ever-increasing livestock numbers and weakly coordinated management (Ulambayar and Fernández-Giménez 2019). There have been widespread reports of rangeland degradation (Addison et al. 2012; Eckert et al. 2015). Nonetheless, tools for assessing the true nature of rangeland change and responding to it did not exist.

State-and-transition model development combined with monitoring and support for community-based rangeland management began in 2008 via cooperation of an international donor organisation (Swiss Agency for Development and Cooperation's 'Green Gold' programme), the Mongolian government and US scientists. Mongolia is fortunate to have government-supported technical staff associated with local governments. Government staff are able to carry out monitoring, use state-and-transition models and participate in community-based rangeland management. Starting in 2009, the Mongolian Green Gold programme scientists were trained in monitoring, model

Limitations

The development of state-and-transition models that are useful for the management of SES is limited primarily by information available on states and transitions and the resources to support collaborative development efforts. Conceptual state-and-transition models developed at broad scales by scientists, usually in one-time efforts, can be useful for education, but they lack participatory and feedback elements that increase the quality of and trust in the models. In addition, people must be willing to use the state-and-transition models. A sense that state-and-transition models could be a waste of time or only add burdensome regulations may thwart development efforts even when resources are available. A lack of data and information on ecosystem responses to management is often a critical limitation. An absence of data or accurate local knowledge will yield state-and-transition models of limited complexity and predictive value, to such an extent that these models are ignored.

Resource implications

Successful conceptual model development requires human and financial resources to support interviews and workshops, literature review and legacy data compilation, new data collection and analysis, and the production of documents. Leaders should foremost have good facilitation

development methods and database management by US Department of Agriculture's Jornada Experimental Range scientists. In 2011, rangeland assessment and monitoring procedures, based on techniques used by US government agencies, were established and Green Gold scientists trained over 400 technicians.

Green Gold scientists and technicians conducted an inventory of vegetation and soils at over 600 sites across Mongolia. These measurements provided an empirical basis for developing state-and-transition models. In addition, workshops were conducted to elicit local knowledge about reference conditions and the presumed causes of vegetation change, and to identify informative sites for additional inventory.

A national core group was established to oversee state-and-transition model development. The core group comprised experienced plant community ecologists representing different ecoregions across Mongolia alongside representatives of science and land management agencies. The core group designated 22 distinct land classes by grouping together finer-grained soil variations (called 'ecological site groups'), for each of which a state-and-transition model was developed. Other tasks included: (a) reviewing published materials to establish reference conditions and causes of state change, (b) working in close collaboration with Green Gold scientists to develop and revise state-and-transition models, and (c) performing outreach activities to encourage the adoption of models by local government and herder cooperatives.

A primary objective of the model development effort was to specify rangeland management strategies to maintain or recover perennial grasses. In contrast to the pre-existing narrative, monitoring data interpreted via state-and-transition

(*Continued*)

models indicated that many sites were not significantly altered from reference conditions and that the majority of them could be restored with changes to grazing management. The core group expanded the state-and-transition models to contain detailed information about recommended stocking rates and grazing deferment periods, tailored to the objectives of either maintaining a current state or recovering a former state. Recommendations and expectations were linked to specific vegetation-cover indicators that could be monitored as part of community-based rangeland management.

In Figure 27.1, plant composition and key plant species are described for each state. At the bottom the estimated above-ground plant biomass yield and resilient carrying capacity (RCC) are displayed, indicating the number of Mongolian sheep units that can be grazed to maintain or improve plant community composition and productivity. Tables (not shown) contain more information about each state and the various transitions.

Today, agencies are using state-and-transition models as part of community-based rangeland management across Mongolia to plan grazing and resting periods. Positive changes in vegetation are occurring where coordinated grazing management has been implemented. In addition, responsible agencies are using state-and-transition models to interpret national-scale monitoring data (at 1 516 monitoring sites) for periodic reporting of rangeland trends to the public via national news organisations. A recently established non-governmental organisation, the National Federation of Pasture User Groups, serves as a coordinating body that promotes the use of state-and-transition models across agencies and herder organisations.

skills. Leaders or key participants should have a background in natural resource ecology (including the precise measurement of natural resources of interest (e.g. Herrick et al. 2017 for rangelands)), geographic information systems (GIS) and statistical analysis, and participatory science approaches. No specific software or techniques are required, although multivariate analysis options in the R programming language are often used (e.g. vegan, labdsv packages).

New directions

The linkage of state-and-transition models to multiple ecosystem services, economic modelling and structured decision-making frameworks are promising recent directions (Fraser et al. 2017; Ritten et al. 2018). In addition, there have been great strides in using machine-learning algorithms on spatial data to generate maps of ecological conditions and state changes (Jones et al. 2018). Maps of states can greatly enhance the use of state-and-transition models for landscape management. State-and-transition models have also been incorporated into interactive computer-based games to help landowners and students learn about concepts of states and thresholds, and to explore the consequences of hypothetical management decisions in a risk-free environment (Ritten et al. 2011). However, all these advances are predicated on high-quality conceptual state-and-transition models.

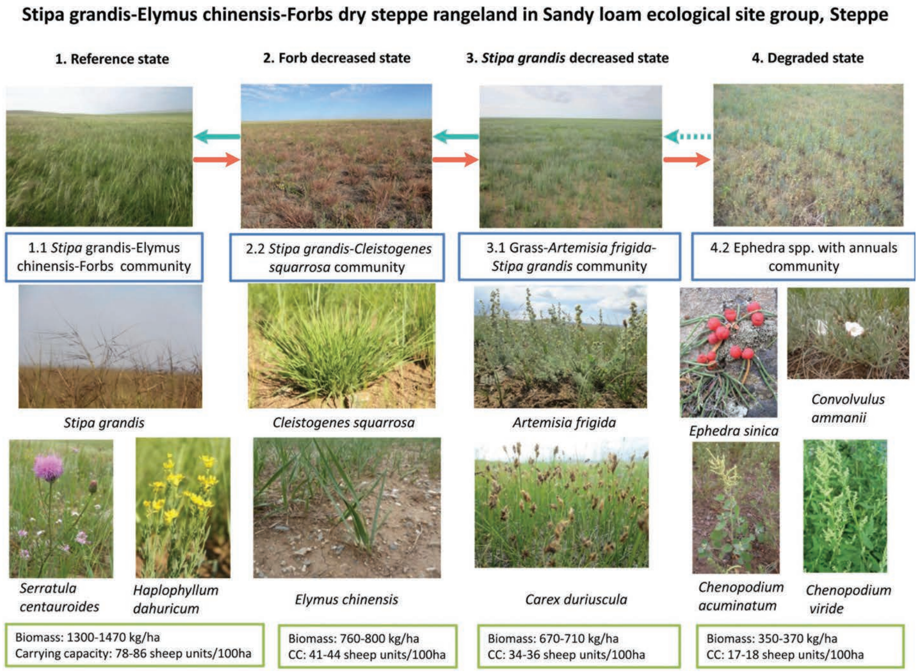

Figure 27.1 An example state-and-transition model for sandy loam alluvial fan soils in the dry steppe of central-eastern Mongolia (Densambuu et al. 2018)

Key readings

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