STATE-AND-TRANSITION MODELS AS GUIDES FOR ADAPTIVE MANAGEMENT: WHAT ARE THE NEEDS?

Modelos de estado y transición como guías para el manejo adaptativo: ¿cuáles son las necesidades?

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Introduction

State and transition models (STMs) were conceived as a means to organize information about land potential and vegetation dynamics in rangelands to be used in their management. The basic idea is simple: describe the plant community states that can occur on a site and the causes of transitions between these states (Westoby et al., 1989). STMs are not bound to any particular theory about how vegetation should change, so they are flexible and able to represent succession, event-driven (non-equilibrial) change, and critical or abrupt transitions to alternative states (Briske et al., 2003). The diagrammatic and narrative portions of STMs synthesize various sources of knowledge about an ecosystem, including scientific results, historical anecdotes, and local knowledge to present a set of explanations and predictions for how ecosystems can respond to natural events and management actions (Bestelmeyer et al., 2009).

Ideally, STMs present simple guidelines for adaptive management (i.e., management by hypothesis testing) that are derived from a broad array of information sources and scientific results. These guidelines can be updated based on monitoring and new knowledge. In this way, STMs can facilitate a shift from rigid prescriptions based on a one-way relationship between science and management toward a constantly evolving set of recommendations based on collaborative learning. An evolving, process-based understanding of vegetation change should be more effective in preserving critical ecosystem services than rigid rules of thumb.

Because of the potential advantages of STMs and a renewed focus by academics on the science-management interface, STMs are being developed with increasing frequency in rangelands and other ecosystems on several continents (Grant, 2006; Zweig and Kitchens, 2009; Rumpff et al., 2011; Davies et al., 2012; Lopez et al., 2013). Many STM examples are, however, intended for communication among researchers rather than use by managers. Notable exceptions occur within the United States where STMs are linked to specific classes of land called "ecological sites" in reports called "ecological site descriptions" (ESDs) (Bestelmeyer et al., 2003). ESDs are now commonly developed for western rangelands of the United States, and are being developed for forest and cropland ecosystems by government management agencies. Current estimates based on completed ESDs indicate that over 2000 different STMs have been developed in the United States (H. Sanchez, personal communication).

Ecological sites are classes of land that differ from one another in potential vegetation or responses to natural and management drivers. Consequently, ecological sites differ in physical factors such as soil profile characteristics, landscape position, or climate and can be delineated spatially based on soil and climate maps of sufficient resolution. ESDs organize a wealth of information about an ecological site, including potential biomass production of plants or functional groups of interest (e.g., forage, crops, and timber), intra-annual patterns of production, wildlife habitat potential, and other ecosystem services. STMs associated with an ESD are able to describe the vegetation dynamics of a particular class of land and, therefore, the services provided by different plant communities and states observed on a site. The site specificity of information and focus on vegetation attributes of management interest has made STMs at the ecological site level attractive tools for decision makers. For example, rangeland specialists with the U.S. Department of Agriculture Natural Resources Conservation Service use ESDs and STMs as a basis for selection and design of management recommendations on ranches.

The utility of STMs for environmental decision making continues to be limited, however, within the ESD framework. Limitations include the information available to develop STMs, the ways in which information is acquired and presented, the willingness of decision makers to consult STMs when they are available, the willingness of scientists to acknowledge the value of managers' anecdotal observations, and our ability to systematize this knowledge. In this contribution, we discuss what we see as the key advances that are making, or that could make, STMs more useful for adaptive management to promote wise environmental stewardship.

1. Clarify reference conditions and "health"

The reference state is either implicitly or explicitly the foundation of STMs. Reference states typically encompass a desired or "healthy" set of ecosystem conditions for society at large, such that the goal of management in the face of transitions to alternative states is to maintain the reference state or to restore it (Fulé et al., 1997; Stoddard et al., 2006). This is because reference states are considered to have the greatest options for provision of various ecosystem services (Bestelmeyer et al., 2009). They are "healthy" because the full complement of historical plant species and the soil development supporting them are intact.

Reference states are usually ascertained using historical information or through measurements gathered in relict areas that have not been transformed relative to historical conditions. In many ecosystems, the societal significance and desirability of the reference state is straightforward when that state is well known and when it simultaneously supports a set of ecosystem services valued by stakeholders. Degradation and recovery of desired conditions can then be measured and connected to the logic of STMs. Degradation that is reversible with management adjustments is represented by shifts among "community phases" *within a single ecological state* (i.e., plant community variants of a state), whereas degradation that is not reversible without active restoration—or for which restoration is impossible—is represented by transitions *among ecological states*. Both can be serious concerns, but the ecological processes involved determine whether we can expect "within state" recovery by changing grazing strategies or if "between state" restoration of a desired plant community will be required.

In other cases, however, there can be difficulties in reconstructing a meaningful reference to guide such management decisions. Some ecosystems are strongly nonequilibrial such that "reference" can potentially compass a wide range of climatically-driven vegetation conditions over which we have little management control (Seaquist et al., 2009) or ecosystems may have been transformed by humans over millennia such that the utility of a particular reference is uncertain (Warren et al., 2001). Even when historical conditions are accepted as a suitable reference, the properties of such conditions may be debatable, including the plant communities present and disturbance regimes (Dussart et al., 2011; Whipple et al., 2011; Lanner, 2012; Williams and Baker, 2012). In still other cases, reference conditions may be regarded as unattainable and therefore of little practical value (Zweig and Kitchens, 2010; Belnap et al., 2012). Finally, the reference state by itself may not, as is commonly assumed, be adequate to preserve biodiversity in some landscapes (Fuhlendorf et al., 2012). For example, persistent, low plant cover states of shortgrass steppe ecosystems associated with prairie dog disturbance are necessary to support some native bird species (Augustine and Derner, 2012).

Consequently, the designation of reference conditions should be based on a broadly collaborative process and take into consideration several factors including history (both recent and evolutionary), the physical processes affecting potential plant communities (climate, soils and topography), a recognition of specific time scales for disturbance and other processes, practicality of use, and the variety of ecosystem services of interest in particular ecosystems. Designating a reference in some circumstances will not be useful and in others it will be immensely useful for guiding and motivating productive management actions.

2. Link alternative states to ecosystem services

While designating a reference state or community phase is sometimes problematic, it is generally straightforward to designate the alternative community phases possible for an ecological site. The identity of known community phases—essentially plant community types—can be ascertained primarily by inventory in which vegetation and related attributes are measured directly. Community phases are then assigned to ecological states based on information about the relatively fast (within-state) dynamics and transitions after which recovery of phases is slow or unobserved.

One way of dealing with the problems surrounding reference states noted above is to build quantitative interpretations about the different ecosystem services provided by ecological states and phases (Raudsepp-Hearne et al., 2010; Koniak et al., 2011). ESDs developed within the U.S. already do this to a limited extent via foraging, wildlife, wood product, and recreation "interpetation" narratives developed for the ecological site. This information, however, is not able to support analysis of the costs and benefits of managing state transitions. To serve that purpose, we need to link more comprehensive information about ecosystem services to each ecological state (Brown and MacLeod, 2011). With such information, the costs of restoring a historical state can be weighed against the change in benefits relative to an existing state. Similarly, the costs of losing a desired state can be communicated in terms of specific variables such as forage provision, species losses, and changes to groundwater recharge rates. Such exercises may reveal that "degraded states" offer important ecosystem services (Mascaro et al., 2012) or make clear the tradeoffs between specific services, such as forage production vs. biodiversity (Fuhlendorf et al., 2012).

The danger lurks, however, that certain attributes of reference states will be overlooked if they are not adequately measured, especially the biodiversity of organisms that are not traditionally the focus of management (Bullock et al., 2011; Reyers et al., 2012). Thus, while it will be useful to communicate about states in terms of ecosystem services, it is prudent to acknowledge our limited ability to comprehensively measure all of them effectively. Historical states may be of value for this reason.

3. Base STMs on process-based logic, testable propositions, and field tests

Although STMs often seek to describe the critical processes involved in ecological dynamics and the mechanisms of transition and restoration, it has proven challenging to convey this information in a logical and useful way (Knapp et al., 2011b). For example, transitions in some grassland STMs are sometimes ascribed to "continuous heavy grazing" without more detailed analysis of the processes by which transitions occur (plant death, lack of recruitment), over what timeframe transitions occur (one year or several decades), the specific indicators of the risk of transition (loss of plant vigor, reduced reproduction rates, indications of erosion), or the management strategies used to prevent transitions given the processes involved (proper timing of defoliation to permit successful reproduction during favorable years). There are several reasons why this richness of detail is missing from models: 1) the information is believed to be too complicated to include and therefore best left to direct interactions between managers and extension specialists, 2) simple lack of effort on the part of model developers, or 3) a lack of detailed knowledge.

These reasons notwithstanding, model developers should strive to include details in a logical way (Briske et al., 2008; Bestelmeyer et al., 2010) in order for STMs to be used and, more importantly, be tested and improved via adaptive management. Even when the specific mechanisms of state transitions (or resilience of a state) are not well understood, they can be postulated by blending local knowledge with the rich body of work in ecological science. This can be aided by the development of general STMs at the level of ecosystem types that are then downscaled to particular ecological sites by including more detailed information. Analysis of historical treatments and new monitoring data can then be used to revisit the hypotheses (and sometimes the general ecological principles underpinning them). For example, shrub-dominated coppice dune states of sandy soils in the Chihuahuan Desert were believed to resist widespread perennial grass recovery based on historical observations and the notion that high erosion rates precluded grass establishment. An unusual sequence of years with high precipitation, and other poorly understood factors, led to a flush of grass recruitment that was unexpected (Peters et al., 2012). The STM for the sandy ecological site has been modified to include this new information. STMs should be regarded as fine-scaled theoretical constructs that synthesize what is known, use that knowledge to generate management hypotheses, and are updated as new knowledge is acquired.

4. Produce maps of ecological states

The use of STMs and ESDs for management is greatly facilitated by linking them to map products. For example, Steele et al. (2012) developed a process by which ecological states are mapped within soil map unit polygons (ecological sites) using high resolution imagery and rapid field inventory. For most types of management, this simple activity creates an essential link between the content in STMs and on the ground actions. Managers need to know "where" to do "what". Furthermore, because the interpretation of multiple STMs for large landscapes can be technically demanding, maps can serve as effective communication tools that simplify STM content for specific problems. For example, researchers constructing maps for ranchers of the Malpai Borderlands Group recoded state polygons representing several state-ecological site combinations to a set of five brush management options: 1) treatment potential across the polygon, 2) treatment potential limited to portions of a polygon, 3) low priority for brush control due to high erosion rates, 4) too few shrubs to warrant brush control but use of fire requires grazing management to promote fine fuels, and 5) no brush control needed but grazing management and fire can prevent encroachment. These simplified, spatially-explicit interpretations of STMs have greatly improved our ability to use them to support decision making. In addition, state maps can serve as a means to reconcile tradeoffs among ecosystem services within a landscape (Nemec and Raudsepp-Hearne, 2013) and to develop landscape-level interpretations based on the identities, amounts, and locations of states with respect to spatial processes such as fire, habitat use, or hydrological connectivity (Bestelmeyer et al., 2011b).

5. Consideration of scale and spatial pattern

Although management decisions, including stocking rates and restoration treatments, are typically made at the level of a site or state map unit (100s of hectares), the cumulative consequences of these actions for wildlife populations, fire behavior, or hydrology are expressed at broader spatial extents (Bestelmeyer et al., 2011a). Furthermore, patterns of ecological states at broad extents can influence the likelihood of site-scale transitions in some cases (Peters et al., 2006; Allen, 2007). Some managers and ecologists have criticized STMs because they lack information about scale and spatial heterogeneity (Fuhlendorf et al., 2012) and therefore represent information at too fine a scale to be useful for landscape (usually wildlife) management. This criticism can be addressed in two ways. First, within STMs, community phases (or structural characteristics within them) could be linked to the habitat preferences of animal species of concern occurring within a region (Holmes and Miller, 2010). Furthermore, spatiotemporal patterns of patchiness in community phases that support suites of species, such as grassland birds (Fuhlendorf et al., 2006), could be described as narratives at the level of groups of ecological sites or perhaps an ecoregion. Second, maps of ecological states (or when possible community phases) can be used to evaluate the cumulative or emergent properties of mosaics of ecological states and the topoedaphic setting. Such maps must ultimately be developed for specific spatial landscape processes, such as animal movement, fire, or hydrology, which will determine the appropriate extent and variables needed. In this context, the role of STMs is to define what management options are available for particular sites and therefore how landscape properties can be manipulated by selecting interventions within specific localities.

6. Use training and technology to make STMs broadly available, understandable, and useable

The idea of using STMs for adaptive management and long-term environmental stewardship rests on several assumptions. The most fundamental of those is that land managers are the most important actors determining resilience and state transitions (and they are most directly affected by them as well). Policies tend to act indirectly on land condition, and in the case of many global rangelands, often weakly so. A further assumption is that information presented in STMs can help managers to select actions that promote desired states. Thus, the information in STM diagrams, documents, and tables have to be *learned* by managers to be useful.

How does this learning occur? The implicit assumption commonly encountered in the U.S. is that 1) extension specialists, consultants, or other professionals will interpret STM documents and communicate management recommendations verbally to managers or 2) managers will interpret information directly from the documents. Neither of these, we feel, is ultimately feasible, especially in developing countries. Current ESDs, with STMs included, are presented as web documents of tens of pages, making them difficult for many users to comprehend. The format of ESDs, the language used, and the technical nature of much of the information is challenging for managers and specialists alike. Finally, it is technically demanding simply to discover which ESD applies to a particular land area, requiring knowledge of soil or climate.

Conveying the information in ESDs to users such that they can guide management decisions is a multifaceted problem that should be more carefully considered by the institutions interested in promoting ESDs. Approaches include 1) collaborative development of ESDs/STMs including managers (or their representatives) who will use them (Knapp et al., 2011a), 2) initiation of collaborative adaptive management projects at the scale of landscapes that include ESD development and use as key components (Bestelmeyer and Briske, 2012), 3) the use of mobile technologies to link users to ESDs pertaining to specific localities (Karl et al., 2012; Herrick et al., 2013), and 4) the distillation of ESD information into simple presentation materials (such as pictorial field guides, web-based materials) and the use of field-based workshops to enable understanding of these materials. The production and use of ESDs and STMs for adaptive management will require concerted efforts by scientists, government agencies, educators, and technical experts and cannot be limited to the production of reports, publications, and associated databases by a handful of managers and ecologists.

Conclusions

The development of STMs such that they can be used for adaptive management will require attention to several core problems including the nature of reference or desired conditions, consideration of the distinct ecosystem services provided by ecological states, development of process-based, logical and testable statements about how states will respond to management, map products that associate interpretations of ecological states to specific land areas, scaling up of maps to address spatial processes at the landscape level, and production protocols, tools, and training that make information available, understandable, and believable to users. Although there may be several ways in which STM development is approached, each of these problems should be considered by model developers. The community of STM developers may then be able to recommend a set of best practices that ultimately yield tighter links between models and adaptive management.

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VARIACIÓN ESPACIAL Y TEMPORAL DEL FLUJO DE ENERGÍA DE PASTIZALES

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Captar, transformar y transferir energía es una de las funciones esenciales de los ecosistemas. Desde temprano en el siglo XX, contamos con un modelo que describe este proceso mediante una serie de flujos parciales de energía entre el sol y las plantas, y entre estas y otros organismos. El modelo actual no ha cambiado esencialmente desde entonces, pero se ha avanzado significativamente en conocer las variaciones de tales flujos parciales en el espacio (regiones, paisajes) y en el tiempo (entre años y estaciones). Estos avances han puesto a su vez en evidencia problemas de conocimiento aún no resueltos. En esta conferencia presentaré los principales patrones de variación espacial y temporal de los flujos de energía dentro de ecosistemas de pastizal con especial énfasis en los niveles de plantas y herbívoros. Presentaré el modelo general y luego mostraré la variación espacial y temporal de algunos flujos importantes: la fracción de radiación absorbida por las plantas, la productividad primaria, el consumo, la asimilación y la productividad de los herbívoros. Para algunos de estos flujos profundizaré sobre los controles ambientales de las variaciones observadas y resaltaré algunos problemas que requieren investigación. Finalmente, presentaré un programa de seguimiento de la productividad de pastizales.