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An Assessment of State-and-Transition Models: Perceptions Following Two Decades of Development and Implementation

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Abstract

State-and-transition models (STMs) are being developed for many areas in the United States and represent an important tool for assessing and managing public and private rangelands. Substantial resources have been invested in model development, yet minimal efforts have been made to evaluate the utility of STMs for rangeland assessment and management. We interviewed 47 rangeland professionals, equally divided between managers and researchers, in four ecoregions to determine their perceptions of the purpose, development, and strengths and weaknesses of STMs to assess the status of the STM framework. Our analysis identified three primary perspectives regarding the purpose of STMs: a decision-making tool for land managers, a means to represent the complex dynamics of rangeland ecosystems, and an effective communication tool. These diverse views of STM purposes were associated with differing perspectives concerning model development that identified five major issues in need of further development and refinement: 1) the relative importance of management practices and ecological processes in driving transitions, 2) the criteria used to define thresholds, 3) the appropriate level of model complexity, 4) the respective roles of expert knowledge and ecological data in model development, and 5) processes for model review and revision. We recommend greater dialogue among researchers and managers to further clarify STM terminology and develop standard protocols for model development and validation. Mechanisms are critically needed to assure peer review and revision of existing models so that STMs are continually updated to reflect current understanding of rangeland dynamics.

Resumen

Los modelos de estado y transición (SMTs) se han desarrollado para varias areas en los Estados Unidos, y representan un instrumento importante para la evaluación y el manejo de pastizales públicos o privados. Para el desarrollo de los modelos se ha invertido considerable recursos, sin embargo, se han realizado esfuerzos mínimos para evaluar la utilidad de evaluación y manejo de los SMTs. Entrevistamos a 47 profesionales en manejo de pastizales, divididos igualmente entre manejadores e investigadores, en cuatro regiones ecológicas para determinar sus conocimientos del propósito, desarrollo, fortaleza, y debilidad del SMTs para evaluar el marco del estado de SMT. Nuestros análisis identificaron tres puntos de vista principales en relación con el propósito de SMTs: una herramienta de toma de decisiones para los manejadores del recurso, una forma para representar la compleja dinámica de los ecosistemas de pastizales, y una herramienta de comunicación eficaz. Estos diversos puntos de vista, del objetivo de STM fueron asociados con diferentes perspectivas sobre el desarrollo del modelo que identifico cinco temas mayores con necesidad de refinamiento y desarrollo: 1) la importancia relativa de las prácticas de manejo y los procesos ecológicos que conducen esas transiciones, 2) los criterios utilizados para definir esos pasos, 3) el nivel apropiado de la complexidad del modelo, 4) los papeles de los datos ecológicos y conocimientos especializados en el desarrollo de los modelos, y 5) los procesos para la evaluación y revisión de los modelos. Recomendamos un mayor diálogo entre investigadores y manejadores para clarificar la terminología de SMT y desarrollar protocolos estándar para el desarrollo y validación de los modelos. Se necesitan mecanismos críticos para asegurar revisiones arbitradas así como la revisión de los modelos existentes para que los modelos de STMs se actualicen continuamente para que reflejen el conocimiento actual de la dinámica de los pastizales.

Key Words: adaptive management, ecosystem management, expert knowledge, local knowledge, monitoring and assessment

INTRODUCTION

State-and-transition models (STMs) were introduced by Westoby, Walker, and Noy-Meir in 1989 as a framework for organizing management information regarding vegetation dynamics on rangelands. These models were less constrained by Clementsian successional theory than the previous procedure for range condition and trend analysis, so they were able to accommodate a broader spectrum of vegetation dynamics (Westoby et al. 1989). Current models are organized as a

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collection of alternative stable states, separated by thresholds, which represent known or anticipated ecosystems that can be supported on individual ecological sites (soil-climate-based land units). Dynamics between and within states can be driven by natural events and disturbances or human activities (Stringham et al. 2003; Bestelmeyer et al. 2004; Briske et al. 2005). This framework has been adopted widely to evaluate ecosystem dynamics and establish management objectives on rangelands in the United States (USDA 2010) as well as internationally (Suding and Hobbs 2009). Growing reliance on STMs as a tool for rangeland management requires that their development, validity, and application continually be evaluated to ensure their continued effectiveness (Briske et al. 2005).

The Natural Resources Conservation Service (NRCS), in cooperation with several other federal agencies, has led development of STMs for ecological sites throughout the United States over the last decade. The five core elements of STM structure (italicized) are standardized (see Briske et al. 2008 and Bestelmeyer et al. 2010 for examples of STMs). *Community phases* are distinctive plant community types that can occur over time within a state and ecological site. *States* represent distinct plant functional groups, process rates, and feedbacks that are separated by thresholds and that group different suites of community phases together. *Community pathways* describe the mechanisms of change between community phases within a state; because they occur within a state they are viewed as being readily reversible through management or successional dynamics. In contrast, *transitions* describe the mechanisms of change between states involving thresholds that preclude recovery of the former state without large inputs of energy. *Restoration pathways* describe the efforts needed, when it is possible, to recover the former state after a transition. In current STMs, each element relates to narrative text and, in the case of states or community phases, photographs of vegetation and data tables pertaining to the productivity, seasonal growth and forage values of vegetation. Current STMs (estimated to number over 2 000 in the United States) can vary considerably in the detail included and format.

In spite of the significant progress in development of STMs, there has been little systematic evaluation of how researchers and managers perceive the effectiveness of STMs. The perceptions of STMs within these two professional groups would be valuable for informing future model development and application. Managers and researchers alike gain knowledge through personal experience and the scientific method, but managers often rely heavily on local knowledge and interaction with landscapes, whereas researchers rely more on systematic data collection and analysis. In this paper, we consider manager knowledge to be a blend of scientific knowledge gained through formal education and professional training, and local knowledge gained through experience as land managers. We use expert knowledge to refer to the knowledge of managers, researchers, and resource users based on their cumulative professional and personal experience. The unique ways in which researchers and managers acquire knowledge can influence their respective assumptions regarding both model construction and application. For example, managers who have long-term experience on specific ecological sites might emphasize management actions and constraints that are most relevant for those sites, whereas researchers might place greater emphasis on ecological mechanisms and ecosystem dynamics supported by the scientific literature and experimental research.

We conducted qualitative, semistructured interviews to investigate how managers and researchers perceive STMs in four ecoregions of the United States where they have been widely adopted: the Chihuahuan Desert Grassland, Sagebrush Steppe, Shortgrass Steppe, and Sonoran Desert Grassland. Qualitative research is recognized as a useful approach in the rangeland profession because it allows researchers to ask questions that cannot be adequately addressed with current quantitative methods (Sayre 2004). We queried participants on their perceptions of the purpose of STMs, terminology and concepts, methods of model construction, STM strengths and weaknesses, and recommendations for model improvement. We anticipated that managers and researchers would differ in their perceptions of STMs, given their distinct means of acquiring and using knowledge. An assessment of current perceptions and assumptions of these professional groups provides an empirical basis for reflection and reassessment at a pivotal time when the STM framework is trending toward greater complexity. Greater model complexity originates from the incorporation of ecological processes and mechanisms associated with transitions, in addition to the experiential knowledge of managers (Suding et al. 2004; Bestelmeyer 2006; Briske et al. 2008; Petersen and Stringham 2008).

METHODS

In each of the four ecoregions selected, we identified experts, including managers and researchers, who were knowledgeable about STMs or actively engaged in model development or application. We asked each participant to identify other knowledgeable individuals in the region to expand our list of potential participants. Ranchers and landowners were not included in this group of experts, because they are not regularly involved in model development, and very few are familiar with STMs (Kelley 2010). We also created a list of potential participants who were not directly affiliated with any of the selected ecoregions, but who are national leaders in the development and application of STMs. Participants were recruited with introductory emails and, if needed, follow up phone calls. We initially contacted 52 individuals and conducted interviews with 47 of them.

We conducted interviews with two categories of individuals: managers, including range managers and federal agency administrators (e.g., regional and technical staff), and ecological researchers. We consider our sample to broadly reflect the perspectives and understanding of the primary groups engaged in the construction and application of STMs. We interviewed ten participants each from the Chihuahuan Desert Grassland (New Mexico: Major Land Resource Area [MLRA] 42), Sagebrush Steppe (Idaho: MLRAs 11 and 25), and Shortgrass Steppe (Colorado: MLRA 67B), eight from the Sonoran Desert Grassland (Arizona: MLRA 41), and nine at-large individuals who are nationally recognized STM experts. The participants from each region were similarly split between researchers ($n = 21$) and managers ($n = 26$). Managers were employed by the NRCS (17), United States Forest Service (USFS; 3), Bureau of Land Management (BLM; 5), and The Nature Conservancy

Table 1. Manager and researcher perceptions of the purpose of state-and-transition models.

STM purpose	Manager (n = 26) No.	%	Researcher (n = 21) No.	%	Total (n = 47) No.	%	Illustrative quotations from transcripts
Guide management decisions	24	92	17	81	41	87	They allow you to think about management within different scenarios … to think about thresholds for management.
Describe ecological dynamics	17	65	16	76	33	70	They provide a summary of our understanding of how ecological sites work.
Communication tool	9	35	9	43	18	38	It's an effective communication tool. It helps … because you can share what you know or think you know about the communities.
Identify testable hypotheses	3	12	16	76	19	40	They're a great tool for designing research and identifying or developing hypotheses, because they're essentially a big set of hypotheses.
Dynamic tool to support adaptive management	3	12	4	19	7	15	They should be a dynamic living document that evolves with time as our understanding improves and as more and more people have the opportunity to contribute to them.

(1), and researchers were affiliated with universities (14), the Agricultural Research Service (ARS; 5), and private consulting firms (2). Ten of our participants were women and the rest were men. Twenty-one of the participants grew up in rural areas, with the other half were equally distributed among urban (7), suburban (7), and exurban (7) areas. Five participants did not provide information about their origins. Sixteen participants held a bachelor's degree, eight had completed master's degrees, and 23 held doctorates. Two-thirds of the participants had at least one range-related degree.

Interviews were semistructured and comprised two categories of questions: 1) those related to ecological dynamics, and 2) those related to perceptions, experience, and understanding of STMs. In this paper, we focus on responses to the second category regarding perceptions of STMs. Representative questions included: 1) What is the purpose of STMs? 2) How would you define key STM concepts, including state, transition, and threshold? 3) Describe how STMs are being developed in your region. 4) What do you think are the strengths and limitations of STMs from a management perspective? 5) What are the strengths and limitations of STMs from an ecological perspective? 6) How can the development and application of STMs be improved? Interviews were conducted in person or by phone over a period of 1–2 h for each participant. Each interview was audiorecorded and later transcribed.

We used a qualitative data analysis program, NVivo, to code the interview transcripts (NVivo QSR revision 1.2, QSR International Pty., Victoria Australia, 1999–2000). Coding is a commonly used qualitative analysis technique that aims to track, categorize, and understand themes of interest in a text, such as an interview transcript (Neuman 2002). We first generated a list of codes (such as "transition definition" and "strength of STMs") based on our broad research objectives, propositions, and the interview questions. After a preliminary round of coding, we expanded our code list based on emergent themes and then conducted a second round of coding to confirm that we had adequately coded each transcript for both the initial and emergent codes. Once the coding was completed, we organized the coded text passages into tables based on the coded themes. This allowed us to consolidate major themes and explore them in order to understand the primary findings related to our research objectives. For each theme, analysis included an iterative process in which we summarized the major findings and then returned to the original coded passages for each thematic code to confirm that we were adequately conveying the messages embedded in the interviews. The results that emerged from this process were summarized. and then the transcripts were reviewed a final time to search for contradictory evidence and to verify the qualitative results that had been derived (Warren and Karner 2005). In contrast to statistical analysis of quantitative data, qualitative analysis of interview data seeks to explore the variation in viewpoints, including rare but important opinions held by a small number of respondents, as well as identifying dominant, widely shared perceptions. The results represent a synthesis of these findings and include both quantitative results (percentage values refer to the population of 47 participants) and illustrative quotations when informative to the analysis.

RESULTS

Purpose of STMs

STMs were most commonly perceived as a tool to guide management decision-making (87%), although managers were slightly more likely (92%) than researchers (81%) to share this perception (Table 1). The second most common response, shared by both managers (65%) and researchers (76%) was that STMs are effective in describing the dynamics of rangeland ecosystems. Participants indicated that STMs are useful tools to communicate both ecological and management information among various stakeholder groups (38%), but they held different perspectives regarding the type of communication for which they were most effective. Of those citing communication as being important, all managers perceived STMs as a tool to provide general understanding of systems to land managers, but only half of the researchers shared this perception. Researchers were more likely to envision STMs as

Table 2. Manager and researcher perceptions regarding definition of state-and-transition concepts "threshold" and "transition."

	Manager (n = 26)		Researcher (n = 21)		Total (n = 47)		
	No.	%	No.	%	No.	%	Illustrative quotations from transcripts
Transitions and thresholds defined by:							
Ecological processes	6	23	8	38	14	30	My number one suggestion is that we change our mindset from [management] practices to [ecological] processes.
Management practices	5	19	2	10	7	15	Here's where you are, you're ranch is here, we want to get it to here, how can we do that [management actions]?
Temporal scale							
Confusion regarding time in distinguishing transitions and thresholds	5	19	7	33	12	26	I think it needs to be a lot more precise in terms, in ecological site descriptions because we're dealing with vegetation that changes on a human timescale and a soil survey was based on the spatial distribution of properties that don't really change on a human time scale
Time can distinguish transitions from thresholds	7	27	2	10	9	19	So that's why it's a time thing. It does recover but the timescale is so slow relative to the timescale of the initial change, that I would call that a major transition.
Time alone cannot distinguish transitions from thresholds	3	12	6	29	9	19	I almost consider the plant community pre- and postfire to still be the same state because it moves over a very long timescale. It can take 100 years to get sagebrush back on some of our burns but there's no … obviously no threshold crossed since it's coming back and there's no manipulation of the system.

a way to identify assumptions that could subsequently be tested through experimentation (40%: researchers 76%, managers 12%). Participants described STMs as an adaptive tool that should change with evolving knowledge about the system (15%), but others expressed concern that although STMs are developed with the intent to be adaptive, lack of time and resources might contribute to institutionalized and static models (21%). The majority of participants (96%) spoke primarily or solely about model applications for grazing management, with few addressing other types of uses or applications of STMs, such as wildlife habitat, invasive species management, or land use planning.

Conceptual Understanding

Participants shared a similar understanding of "state," but diverged in the way they defined "threshold" and "transition." State was consistently defined as a distinct and stable plant community and its associated soils (79%). Although participants gave common definitions of "state," few cited published and academically accepted definitions and several demonstrated that current published definitions were either unknown or not used.

Participants had more varied interpretations of the meanings of the terms "transition" and "threshold," and the differences between them (Table 2). Inconsistencies among respondents emphasized two major issues: 1) whether transitions and thresholds should be defined primarily by ecological processes (30%) or management practices (15%), and 2) the role of temporal scale in defining transitions and thresholds. Researchers (38%) were slightly more likely than managers (23%) to indicate that it is important to include ecological processes in transition descriptions, although both groups discussed the inclusion of ecological processes. The opposite was true for management practices, with managers (19%) expressing the importance of including practices slightly more often than researchers (10%). Participants perceived that it is possible to incorporate both processes and practices in transition and threshold concepts, but disagreed about their relative importance.

A quarter of participants (26%) expressed confusion about the role of temporal scale in determining whether a change in vegetation should be classified as a transition (involving a threshold) or a community pathway (that does not involve a threshold). Some participants used time to gauge transitions (19%), but an equal number indicated that time should not be used to define transitions (19%). Some perceived that a transition should be recognized if change is not reversible "within a management timeframe" or if recovery takes a very long time (19%: manager 27%, researcher 10%). Participants defined "management timeframe" differently, but most agreed that changes that take 20–30 yr or more are outside of a "management timeframe." Others perceived a threshold to exist only when recovery is impossible, as when site potential is permanently altered by soil loss (19%: manager 12%, researcher 27%). Managers (27%) were more likely than researchers (10%) to use time as a factor in defining transitions, whereas researchers (29%) were more likely than managers (12%) to assert that it should never be used. Several of the researchers (16%) raised this issue explicitly in their interviews; one researcher remarked, "The discussion of time needs to take place within the theoretical context of the models … There can be management thresholds that are not technically thresholds and those are things we need to start discussing." This respondent was asserting that changes that might be irreversible in a management timeframe, and thus constitute "management thresholds," are not necessarily thresholds in the strictly

Table 3. Manager and researcher perceptions of model construction, validation, and review.

Model attributes	Manager (n = 15)[1] No.	Manager %	Researcher (n = 8)[1] No.	Researcher %	Total (n = 23)[1] No.	Total %	Illustrative quotations from transcripts
Expert knowledge is a critical resource	7	47	3	37	10	43	He's familiar with all of the northeast area and pretty much all of the foothills area and even into the mountains. He's just got a wealth of information and so the two of us together have most recently been working on [ecological site description].
Concern about using expert knowledge as sole resource	5	34	5	61	10	43	My perception is not always right. I'm a human being, I see things and I have my own realm of experience and all that sort of thing and eyeballs are qualitative sort of a thing and so qualitative models are also qualitative and subject to the same sort of error as all human types of things. It has to be validated with real data.
Frustration with the lack of data	5	34	6	76	11	48	[State-and-transition models don't] really have a strong scientific basis and so I think long term datasets and really utilizing quantitative methods for defining states and/or transitions, I think that would really help strengthen the models.
Concern with lack of consistency in model development	5	34	1	13	6	26	I would say it [model development] varies mostly by state. I guess … to sort of verbalize natural ecological regions but still within the physical boundaries of a state.
Mechanism for model validation	13	87	7	88	20	87	We've identified a research project or a study or another data set that we've got to go out and see if we can reconcile this difference of perspective and then go from there.
Validation is limited or minimal	8	53	1	13	9	39	Some people look at it [draft state-and-transition models] a little bit but it [the review] was nothing extensive.
No validation or review	2	13	1	13	3	13	I wrote other site descriptions and developed these other conceptual models that I could send to and get feedback from and I never got any feedback from anybody.

[1]Numbers reflect participants actively engaged in model creation.

defined sense of irreversible changes in site potential or ecological function.

Model Construction, Validation, and Revision

One-half of the participants interviewed were directly involved in model construction (49%). They described the process of model development as relying primarily on expert knowledge and older range site descriptions, with inclusion of historical records, data from relict vegetation, published research, and monitoring data when available. Nearly half of the respondents felt that expert knowledge (including local knowledge) is a critical resource for model development (Table 3) (43%: researcher 37%, manager 47%). These respondents related that expert knowledge is the fastest and easiest way to develop models, especially when long-term experts reside in the area. Respondents indicated that expert knowledge can offer valuable insights concerning system dynamics and issues of management concern, and provide information describing events that might be unaccounted for by formal research studies. One researcher explained how expert knowledge could identify events that might not otherwise be captured in data collection saying, "[A primary challenge is] getting the data. Finding the places that have good data. I mentioned already the [ability of expert knowledge to identify] low probability but widespread events." Participants felt that expert knowledge was able to fill in gaps where other types of data were unavailable. However, participants also expressed hesitation about using expert knowledge as the sole resource for STM development (43%: researcher 61%, manager 34%). Participants from both groups felt that expert knowledge could be inadvertently biased or incomplete. As one researcher stated, "My perception is not always right. I'm a human being, I see things and I have my own realm of experience … It has to be validated with real data."

Participants, including both researchers (76%) and managers (34%), expressed the importance of including ecological data from observational or experimental field studies in model construction and articulated their frustration with the lack of data. As one participant stated, "I think that there is a general lack of data. I think that there are a lot of people that have worked in the system for a long time who have a lot of ideas about how the system works, but I don't really think there has been a lot published." Several participants (9%) spoke explicitly about the need to include both expert opinion and empirical data, and were concerned about reliance on either information source alone. As one manager stated, "We're overbalanced, if you will, on expert knowledge without the data … In some models, it might go the other way and overbalance data without the knowledge and it's really easy to replace data with experience or experience with data. Let's try not to let the pendulum go all the way. Let's stop it somewhere in the middle."

Participants expressed concern over the lack of consistency in model construction (26%: manager 34%, researcher 13%). One manager explained, "I would say it [model construction] varies mostly by state within the US." The period during which models were constructed, the status of STM theory and application, the sources of available data, and the people involved in model construction varied among the four ecoregions studied. As one at-large manager explained, "I think you need to keep it in context because they (STMs) were in a different place and the theory was in a different place." STM theory and concepts have developed greatly in the past 20 yr, and the early models in some ecoregions were published prior to the most recent developments. Although a standard protocol currently is being developed, past model development has had little consistent direction. In the course of interviews, we asked participants who had developed STMs whether and how they validated their models. Most participants who had developed models described some type of validation process (87%), although a portion stated that it was limited or minimal (39%), and several indicated that peer review was not sought (13%). Model validation consisted of a review by regional experts and sometimes university researchers; however, very few (9%) model authors we interviewed received substantial feedback following model construction. Thus, the validation processes that model developers described are more akin to an informal peer review process in which the reviewers were expected to evaluate the models against their experiential knowledge, scientific data, and knowledge of the published literature. It did not constitute model validation in the sense of testing the model by collecting and analyzing additional independent field data to determine if the model accurately predicted the results of empirical data. Similarly, current models do not include estimates of the certainty associated with the states and transitions described.

Despite concerns about the availability of data, several (14%) researchers interviewed indicated that there is no clear process for incorporating uncertainty and emerging knowledge into STMs. As one researcher stated, "Most of the transitions in those models will take decades and a whole team of people to address. So it's very complex, but I think at the same time, there are certain transitions and certain arrows in those models that have been well-studied and where the studies conflict with what the model says. There is no acknowledgement of that and I don't see a process for … updating those." Other participants (21%) expressed concern that limited staff time would minimize model improvement even if additional information became available.

Strengths and Weaknesses of STMs

We asked participants about the strengths and weaknesses of STMs from an "ecological perspective" and a "management perspective." Participants defined two primary *ecological strengths* of STMs: 1) their ability to depict current understanding of system dynamics (70%), and 2) the capacity to identify relevant questions or hypotheses regarding system dynamics (34%; Table 4). Researchers (52%) often discussed how models encourage explicit identification of assumptions and relevant questions concerning systems of interest. Participants broadly referenced three *management strengths*, including 1) improved decision-making (87%), 2) improved communication (38%), and 3) the facilitation of adaptive management (15%). Managers (92%) were slightly more likely than researchers (81%) to cite improved decision-making as a strength of STMs, but both groups placed a high value on this purpose.

Participants described three *ecological weaknesses* of STMs: 1) their lack of information regarding ecological processes (23%), 2) limited or nonexistent empirical evidence to determine states and transitions (15%), and 3) a rigid structure that may foster misrepresentations of ecological dynamics (17%). The concern regarding misrepresentation arose from the perception that an emphasis on multiple states and thresholds in the STM framework might encourage some model developers to include them even when the ecosystem under consideration does not demonstrate alternate states and threshold dynamics (17%: manager 8%, researcher 29%).

Participants emphasized three general *management weaknesses* of STMs: 1) insufficient information to guide management (43%), 2) unnecessarily complex models (26%), and 3) lack of time and resources to develop models (21%). Participants were concerned that the absence of specific types of information potentially could limit the management effectiveness of STMs. This information included timeframes, probabilities, economic costs and benefits, interactions between adjacent ecological sites, management actions other than grazing, underlying ecological processes, threshold indicators, drivers of system change, and the potential impacts of climate change. Although a quarter of participants indicated that model format should be as simple and streamlined as possible (26%: managers 38%, researchers 10%), others felt that models should encompass the full complexity of ecological dynamics to provide the most complete information possible (10%: managers 4%, researchers 19%). Finally, participants were concerned that a scarcity of time and resources would lead to static models that are not regularly updated and adapted to reflect changing knowledge (21%).

Several (11%) participants were concerned that models were being accepted as definitive interpretations, rather than as working hypotheses based on the best information available at the time. Overconfidence in models might lead inexperienced managers to rely on models exclusively and discount their own experiential knowledge of the system. As one participant stated, "Sometimes you can be led into a false sense of security when you say okay, I've got this community that I'm looking at and it's definitely crossed a threshold. Well, has it really"? This false sense of security in STMs might dissuade some managers from developing their own experiential knowledge of systems and thus reduce their effectiveness in adjusting management in response to changing environmental cues. In addition, a few participants (6%) were concerned that models seen as "statements of fact rather than working hypotheses" might be misapplied in a regulatory context.

Researchers and managers both suggested that models would benefit from better communication among STM developers, disciplinary specialists within management agencies, researchers, and end users (19%). Model developers spoke of the need for interdisciplinary development teams, including expertise in rangeland science, restoration, wildlife ecology, soil science, and hydrology, to interact and coordinate development of STMs, so that they encompass the diverse information needed for effective ecosystem management.

The most common suggestion to enhance the effectiveness of STMs was the establishment of a standardized process for

Table 4. Manager and researcher perceptions regarding the strengths and weaknesses of state-and-transition models.

Model strengths and weaknesses	Manager (n = 26) No.	Manager (n = 26) %	Researcher (n = 21) No.	Researcher (n = 21) %	Total (n = 47) No.	Total (n = 47) %	Illustrative quotations from transcripts
Strengths							
Represents knowledge of system dynamics	17	65	16	76	33	70	I think the models that we have now, state and transition models, explain what's going on to the best of our abilities.
Identifies relevant questions	5	19	11	52	16	34	[They are good for] pattern detection so that you can then ask good questions and devise research to answer those questions.
Improves decision making	24	92	17	81	41	87	I see the value of the state and transition model to assist [landowners] in understanding the processes that are taking place and then how they can affect those processes on a particular ecological site.
Improves communication	9	35	9	43	18	38	I think first and foremost they're a graphical representation that allows you to communicate important aspects of ecosystem dynamics to people.
Facilitates adaptive management	3	12	4	19	7	15	It's a potentially powerful tool in the adaptive management tool kit because it says "here's our current understanding" … so it provides a vehicle to record and upgrade as new information and knowledge and understanding comes online.
Weaknesses							
Ecological processes omitted	5	19	6	29	11	23	A weakness is probably that we don't even have ecological processes described on there. We have the disturbances that are affecting the ecological processes but we don't say, okay, well this symbol here means the hydrologic function and it's affected in this way, you know, negatively or positively.
Weak empirical evidence	3	12	4	19	7	15	Unfortunately the sites that have long-term ecological data so we can construct quantitative models are ridiculously limited.
Might misrepresent ecological dynamics	2	8	6	29	8	17	I resent or I fight that this whole notion that it works in this really tight little way and we really only on a [ecological site name] we only have four potential states and these are the transitions. I think it's more complex than that.
Insufficient information to guide management	8	30	12	57	20	43	From a management side, I would say probably the biggest weakness is the lack of economic connection to what it costs for making repairs to alternative states and trying to either rehabilitate or restore an area back into wherever the reference state would be. We lack that kind of information.
Overly complex	10	38	2	10	12	26	Yeah, well you get one that's got 15 states and they've got arrows going in every direction and it's really difficult to communicate that.
Lack of time and resources for model development	7	27	3	14	10	21	You are pressed for time and we're all pressed for time and only have so much, so many hours in the day to do what we need to do.

constructing and revising STMs (26%: managers 27%, researchers 24%). Managers and researchers were concerned not only about development, but also about the long-term maintenance and revision of models (15%), and a couple (4%) recommended the development of a mechanism capable of coordinating and revising STMs on a central website.

DISCUSSION

Both researchers and managers perceive STMs as an effective means to synthesize existing knowledge of ecological dynamics, guide management decisions, and communicate with multiple stakeholders. Both groups value STMs as a management tool, but many researchers also perceive them as a tool to identify research questions regarding the dynamics of complex systems. Although both groups of participants envision STMs as an important communication tool, the subtly divergent goals and applications between groups mighty lead to different interpretations of how models should be developed and implemented. Managers prefer that models remain sufficiently simple to communicate effectively with landowners, whereas researchers desire models that reflect ecological dynamics as completely and accurately as the data allow, even if this contributes to more complex models that might be more difficult to understand. Distinct interpretations of appropriate model complexity led several participants to suggest the development of separate management and research models. The more complex research models could serve as the repository for all current information for an ecological site description whereas more management-friendly models would represent only the most relevant subset of this information base. A critical drawback of this approach, however, is the potential disconnection of scientific understanding of ecological processes, local knowledge, and the consequences of management actions. For this reason we do not recommend a dual model approach.

A portion of the participants indicated that current STMs fail to fully describe how management practices influence and interact with ecological processes, but others suggested that management practices could serve as a proxy for ecological processes. This divergent interpretation might arise in part from the wide use of two-letter practice codes (e.g., PG for prescribed grazing) assigned to model transitions. These abbreviated codes often fail to describe how management practices affect or are affected by ecological processes because they provide very generic descriptions of practice implementation. These codes can provide an entry point for managers to discuss specifics with landowners or permittees; however, the lack of detail regarding practice implementation makes it difficult to evaluate and learn from either successful or unsuccessful outcomes of various management practices. Previous research has demonstrated that experiential knowledge often focuses on proximate concerns for management (herds or vegetation), rather than underlying ecological processes (Bollig and Schulte 1999). Because the vast majority of STMs have been developed primarily with experiential knowledge, they are likely to omit explicit causal relationships between management practices and ecological processes. This argues for the development and incorporation of a comparable set of ecological processes (e.g., accelerated soil erosion, reduced infiltration, and increased runoff) that could be assigned to community pathways and transitions as appropriate, with their own specific codes. This is relevant especially to STMs because there is increasing interest in identifying the primary ecological processes that function as feedbacks that maintain states, or that are associated with transitions between states when feedbacks are altered (Stringham et al. 2003; Briske et al. 2005).

Understanding of the cause–effect relationships between ecological processes and management practices can influence both the development and application of STMs. If transitions between states are exclusively associated with management practices (e.g., shrub removal or seeding), without attempting to identify the underlying ecological functions, STMs will not effectively inform users of how specific management practices or actions are likely to affect desired or unanticipated outcomes. This will deprive managers of critical knowledge necessary to "fine tune" their management practices and evaluate alternative management actions. On the other hand, if STMs describe transitions in terms of ecological processes independently of management practices, then managers might find it difficult to use them for decision-making. Ideally, STMs should explicitly describe how specific management practices affect, and are affected by, various ecological processes and contexts so that users understand why specific practices are recommended and why they are likely to succeed or fail in various circumstances. A major challenge to achieving this goal is that scientific evidence verifying the success or failure of specific management practices is lacking for many ecological sites. Further, recent research demonstrates that management actions and ecological processes might not always be clearly linked with specific states and transitions, suggesting that practice–process–transition relationships could be difficult to interpret and predict (Kachergis et al. 2011). Systematic approaches to and support for monitoring to document the outcomes of management actions and practices are the most effective procedures for generating knowledge of practice–process–outcome relationships.

Participants emphasized an important temporal distinction in the way system dynamics are interpreted and thresholds are recognized—some understand thresholds to occur only when irreversible change has occurred (e.g., loss of soil that represents a permanent loss of site potential), whereas others assume that the duration of state change alone could differentiate a community pathway from a state transition regardless of its eventual reversibility. This emphasizes that temporal dynamics need to be described when possible to provide greater insight into the role of time when interpreting transitions and thresholds (Briske et al. 2006).

Participants expressed a desire for greater guidance and clarity of construction rules associated with the development of STMs. Conceptual advances have occurred in model structure since the initial introduction of the STM framework (Stringham et al. 2003; Briske et al. 2008), but these advances are not widely recognized or adopted by model authors and practitioners. Current development of an interagency manual on ecological site development, involving the NRCS, BLM, and USFS will further clarify construction rules to inform model development. As with any emerging concept or management framework, consistency and effectiveness develop through time as both concepts and models are tested and refined. However, it is important that construction rules balance model consistency with the capacity to revise and adapt STMs to reflect new knowledge and the occurrence of novel conditions. Development of comprehensive STMs requires integration of all sources of credible knowledge to interpret and anticipate site dynamics, which requires a procedure to incorporate new knowledge as it becomes available. Participants expressed concern that the initial STMs would be adopted as standard agency guidelines that would not be revised as new information became available.

Rangeland management always has attempted to bridge the endeavors of science and management (Provenza 1991), yet the profession is only beginning to explicitly discuss the relative strengths and limitations of knowledge gained through experience, experimentation, and monitoring (Boyd and Svejcar 2009; Knapp and Fernandez-Gimenez 2009; Briske et al. 2011). Consequently, researchers and managers alike might erroneously over- or undervalue their primary knowledge sources. Increased recognition of the complexity of ecosystem dynamics requires that we routinely reassess the knowledge and assumptions on which management decisions are based (Boyd and Svejcar 2009; Briske et al. 2011). Both normative reasons (equity, trust, empowerment, and fairness among knowledge holders) and pragmatic ones (more complete, useful, reliable, and durable knowledge) exist to integrate various knowledge sources, specifically experiential and scientific knowledge (Reed 2008). Reliance on either managerial experience or science alone can lead to incomplete or invalid interpretations (Wynne 1996; Hudak 1999; Mackinson 2001;Tibby et al. 2008; Briske et al. 2011), whereas integration of distinct knowledge sources can provide complementary information that might not be available through other means (Knapp et al. 2011). If the rangeland profession values both knowledge gained from management experience and scientific inquiry, we must explicitly define their relative strengths, weaknesses and uses so that both can be meaningfully integrated into the STM framework.

MANAGEMENT IMPLICATIONS

This assessment of researcher and manager perceptions of STMs describes the current status of STMs and provides direction for future model development and application. Increased interaction among researchers from multiple disciplines, among managers with different natural resource interests and experiences, and between researchers and managers, will strengthen model development, application, and evaluation. This will enable managers and researchers to share their interpretations of the goals of STMs and determine how models can be developed to incorporate both management and scientific knowledge. It is important to communicate a shared understanding of recent conceptual advances associated with STM construction among model developers, managers, and other users to provide a more consistent model structure. A clear need exists for explicit discussion and guidance regarding 1) temporal scales associated with transitions and thresholds and 2) how ecological processes, in addition to management practices, should be incorporated as drivers of ecological dynamics. The rangeland profession needs to clarify the appropriate roles of expert knowledge and ecological data in the construction and application of STMs. Finally, it is critical that model developers have greater access to peer review and that a formal mechanism be established to revise existing models as new knowledge is acquired to ensure that STMs represent the most current knowledge available.

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