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Opportunities for Increasing Utility of Models for Rangeland Management

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Abstract

A large number of empirical and mechanistic simulation models and decision support tools have been produced for rangelands. Collectively, these models have considerably increased our fundamental knowledge and understanding of the dynamics of ecosystem functions, processes, and structure. We explore three areas where models for rangeland management are often challenging for land managers and enterprise-level decision making: 1) coping with spatiotemporal and climatic variability in implementing scenario forecasting, risk assessments, and adaptive management; 2) addressing outputs of multiple ecosystem goods and services and determining whether they are synergistic or competitive; and 3) integrating experimental and experiential knowledge and observations into decision making. Increasing the utility of models for rangeland management remains a key frontier and a major research need for the modeling community and will be achieved less by further technical advances and model complexity and more by the use of existing topoedaphic databases, the capacity to readily incorporate new experimental and experiential knowledge, and the use of frameworks that facilitate outcome-based, adaptive decision making at the enterprise level with associated economic considerations. Opportunities exist for increasing the utility of models for decision making and adaptive rangeland management through better matching of model complexity with enterprise-level, decision-making goals. This could be accomplished by incorporating a fundamental understanding of herbivory, fire, and spatiotemporal interactions with weather patterns that affect multiple ecosystem functions. Most important, effective models would allow land managers in a changing and variable climate to 1) evaluate trade offs in producing multiple goods and services, 2) optimize the application of conservation practices spatially (comparing costs and benefits accrued across different timescales), and 3) incorporate manager capacity, including experience, skills, and labor input.

Resumen

Se ha producido un gran número de mecanismos empíricos, modelos de simulación y herramientas para apoyar la toma de decisiones para los pastizales. En conjunto, estos modelos han incrementado considerablemente nuestro conocimiento fundamental y entendimiento de la dinámica de la función de los procesos y estructura de los ecosistemas. Exploramos tres áreas donde los modelos para el manejo de pastizales son regularmente un reto para los manejadores de pastizales y los niveles de toma de decisiones en las empresas: 1) en conjunto con espacio-tiempo y variabilidad climática en la predicción de escenarios, evaluación de riesgos y la implementación de manejo adaptativo, 2) enfocándose a las de salidas de múltiples bienes y servicios de los ecosistemas, y si estos son sinérgicos o compiten entre sí, e 3) integración del conocimiento experimental y experiencial y observaciones dentro de la toma de decisiones. Incrementar la utilidad de modelos para el manejo de pastizales permanece como una frontera clave y una necesidad e investigación muy importante para modelar la comunidad, y se logrará mediante nuevos avances técnicos y menos complejidad de los modelos y más aun mediante el uso de base de datos topoedáficos existentes, la capacidad para fácilmente incorporar nuevos conocimientos experimentales y experienciales, y el uso de marcos de referencia que faciliten los resultados, la toma de decisiones adaptativa en los niveles empresariales con las consideraciones económicas asociadas. Existen oportunidades para incrementar la utilidad de los modelos en la toma de decisiones y en el manejo adaptativo de los pastizales mediante un mejor ajuste de la complejidad del modelo con nivel empresarial y las metas en la toma de decisiones. Esto puede hacerse mediante la incorporación de un entendimiento fundamental de las actividades de los herbívoros, fuego e interacciones espacio- temporales con patrones climáticos para afectar las múltiples funciones del ecosistema. Mas importante aun, modelos efectivos podrían permitir a los manejadores de tierra en un cambiante y variable clima a 1) evaluar las ventajas y desventajas en la producción de múltiples bienes y servicios, 2) espacialmente optimizar la aplicación de prácticas de conservación (comparando los costos y beneficios acumulados atreves de diferentes escalas de tiempo), y 3) incorporar la capacidad de los administradores incluyendo experiencia, habilidades y mano de obra.

Key Words: climate change, decision making, enterprise levels, experiential and experimental knowledge, object modeling systems, state-and-transition models

INTRODUCTION

Sustainable use of rangelands for multiple ecosystem goods and services involves application of best management practices on complex landscapes to address multifaceted problems (Boyd and Svejcar 2009). Rangeland management, however, can be hindered from the scientific point of view because knowledge

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obtained from traditional experimentation on management practices is often constrained by single factor experiments conducted at small scales (Svejcar and Havstad 2009). Additionally, incorporating the "art" of rangeland management into decision making at the enterprise (e.g., ranch) level involves nuances of human dimensions and experiential knowledge that is poorly integrated with experimental understanding (Stafford Smith et al. 2007; Briske et al. 2011). Using models can provide land managers with the concurrent opportunity to overcome these limitations (Hanson et al. 1999; Weisberg et al. 2006) and to integrate field-experiment research with model parameterization, calibration, and validation (Ahuja and Ma 2011).

Many empirical and mechanistic simulation models (what-if models that attempt to forecast likely outcomes) and decision support tools (computer-based interactive information systems that support decision-making activities) have been produced for rangelands (reviewed in Hanson et al. 1999), with several in wide use (see Table 1). Collectively, these models have increased our fundamental knowledge and understanding of the dynamics of ecosystem functions, processes, and structure considerably. They enable us to compare alternative management approaches, develop scenario forecasts, and facilitate the scaling-up of monitoring and assessment information for regional and national inventory efforts. Besides enhancing understanding of complex interactions of multiple factors, models have helped to extend short-term, localized experimental research results to longer-term weather conditions and broader landscapes (Andales et al. 2005, 2006).

Despite the contribution of rangeland models to our understanding of ecosystem structure and function, models are still rarely used to assist land managers with decision making because of communication gaps between scientists and managers (e.g., Silvert 1989), lack of involvement by decision makers in the model development, and inconsistent terminologies (Schmolke et al. 2010). The complexity and computational requirements of these models may prevent individual land managers and livestock producers from using them (Bunnell and Boyland 2003; Weisberg et al. 2006). Moreover, many of the models lack the capacity to handle livestock movement among different pastures for an enterprise, often require large amounts of data input from the individual land manager, use default or generic parameters that may not be suitable for the location of interest, often lack a user-friendly interface for input of data and model output visualization, and have spatial limitations on how the distribution of vegetation and soils affects livestock grazing behavior (see Table 1). For example, models addressing whole enterprises (e.g., AusFarm Model in GrazPlan; Table 1) are highly complex, thereby requiring significant training and interpretation, which reduces the utility for individual land managers making decisions.

Three areas where models often lack utility for land managers and enterprise level decision making are 1) coping with spatiotemporal and climatic variability in implementing scenario forecasting, risk assessments, and adaptive management; 2) addressing outputs of multiple ecosystem goods and services and whether they are synergistic or competitive, and 3) integrating new, experimental and experiential knowledge and observations into decision making. Although there are challenges to increasing the utility of models for rangeland management, the primary focus of this article is to highlight opportunities for greater utility. We have divided these opportunities into three sections: 1) incorporating spatiotemporal and climatic variability into models for enterprise flexibility (Boone and Wang 2007; Freier et al. 2011; Nozieres et al. 2011); 2) combining contemporary modeling needs, including decision making for multiple ecosystem goods and services (Boone et al. 2011); and 3) integrating new experimental and experiential knowledge into models to predict ecosystem responses in ways that are relevant to decision making by livestock producers, including resulting economic outcomes (Nelson and Robinson 2009). Each section provides justification for these opportunities, primarily related to decision making and adaptive rangeland management, as well as a realization of the need for enterprise-level decision making with spatially explicit knowledge to optimize desired outcomes and reduce risk.

INCORPORATING SPATIOTEMPORAL AND CLIMATIC VARIABILITY INTO MODELS

The directionality, magnitude, and uncertainty of climatic variability and spatiotemporal aspects clearly have management implications (Morgan et al. 2008; Cobon et al. 2009). Furthermore, climate change predictions at regional and local scales are making advances with downscaling global climate models (Charley and Nurse 2010; Maraun et al. 2010; Wilks 2010), but considerable refinement is needed. Thus, it is critically important to determine which strategies sufficiently adapt management systems to spatiotemporal heterogeneities of rangeland conditions, variable and changing climate conditions, and different outcomes, goals, and objectives of livestock producers. Although many models have been developed to investigate generic management issues, such as grazing (see overview in Tietjen and Jeltsch 2007; Wiegand et al. 2008), Teague et al. (2009) note there are few modeling studies that explicitly explore the consequences of spatiotemporal and climatic (both intra-annual and long term) variability on rangeland management. Some exceptions are the Ebrahimi et al. (2010) and Jakoby et al. (2010) model development and application efforts, which render in-depth analysis of spatial effects in grazing management possible (through spatiotemporal simulation of vegetation and grazing interactions). An important research topic for the future, especially as new rangeland models comprising high-spatiotemporal resolution are developed, involves quantifying the optimal degree of complexity for spatially explicit representation of rangeland systems.

To further address spatiotemporal and climatic variability, efforts should be made to link rangeland models with geographic information systems (GIS). The Rangeland Hydrology and Erosion Model (RHEM; Nearing et al. 2011) was recently incorporated into the Automated Geospatial Watershed Assessment (AGWA) GIS-based decision support tool (Goodrich et al. 2011) for improved spatiotemporal rangeland management at field-to-watershed scales. Similarly, SAVANNA (Coughenour 1993) is a spatially explicit ecosystem model linked to GIS, which allows for inputs and outputs to be represented across landscapes and enables modeling of

Table 1. Description, strengths, limitations, and key references for some rangeland models and decision support tools.

Model	Key references	Model description	Strengths	Limitations
GrazPlan	Donnelly et al. 1997; Freer et al. 1997; http://www.grazplan.csiro.au/?q=node/35	Decision support tools for livestock production (GrazFeed), forage production (GrassGro), probable weather conditions (MetAccess), and agricultural enterprises (AusFarm)	Uses daily time steps for probable weather conditions to assist in decision making at critical times in production cycle; assesses risk of different combinations of pastures and animals for soil and climatic conditions	High parameterization requirements for new locations; significant training and interpretation needed for single enterprise (GrassGro) and whole farm/ranch enterprises (AusFarm); lacks Web-based user interface
Great Plains Framework for Agricultural Resource Management (GPFARM-Range)	Shaffer et al. 2000, Andales et al. 2005, 2006; http://www.ars.usda.gov/services/software/download.htm?softwareid=234	Decision support tool for rangeland forage growth and livestock production	Allows users to evaluate scenarios based on current knowledge and future uncertainty in weather patterns	Does not simulate livestock movement among different forage types/pastures; high parameterization requirements for new locations; lacks Web-based user interface
Simulating Production and Utilization of Rangeland (SPUR)	Wight and Skiles 1987; Baker et al. 1992; Carlson and Thurow 1996; Foy et al. 1999; Teague and Foy 2002; http://dino.wiz.uni-kassel.de/model_db/mdb/spur.html	Simulation model of rangeland forage, production, and use and livestock weight gains	Validated for predictions of soil moisture, forage production, and livestock gains for several sites in the US Great Plains; mechanistic simulation of trade-offs among forage quantity vs. quality, forage intake rate, and digestive processes	Does not simulate livestock movement among different forage types, patches, or pastures; high parameterization requirements for new locations
SAVANNA	Coughenour 1993; Boone et al. 2002; http://www.nrel.colostate.edu/projects/savanna/	Simulation model of feedbacks between plants and herbivores in relation to soils, topography, and weather patterns in grassland and savanna ecosystems	Spatial representation of all key ecosystem components and most processes controlling rangeland ecosystem structure and function; can simulate multiple ecosystem goods and services, including livestock, wild herbivores, runoff and soil erosion, ecosystem carbon stocks at weekly time steps, and user-selected spatial scale	High parameterization requirements for new location/ecosystem; experts required for model fitting, incorporation of local knowledge, and scenario testing; herbivore distribution based on Habitat Suitability Index rather than mechanistic representation of foraging behavior and digestive processes
Ecological Site Descriptions (ESDs) and associated State and Transition Models (STMs)	http://esis.sc.egov.usda.gov/	Rule-based models of ecosystem states and forage production based on soils and management and disturbance history	Available for many ecological sites in North America; STMs readily modified to incorporate local knowledge; Web-based user interface	Does not simulate or predict livestock distribution or weight gains; requires detailed field-mapping of existing vegetation states within ESDs
Rangeland Hydrology and Erosion Model (RHEM)	Nearing et al. 2011; http://dss.tucson.ars.ag.gov/rhem	Event-based derivation of the WEPP model developed by incorporating new splash erosion and thin sheet-flow transport equations derived from rangeland data	Web-based user interface; process-based estimation of runoff, erosion, and sediment delivery rates and volumes on rangelands; links model parameters with rangeland plant communities through a new set of parameter-estimation equations based on extensive plot data	Does not simulate livestock movement among different forage types, patches, or pastures; applicable only at the hillslope spatial scale and for single rain-event temporal scales
Water Erosion Prediction Project (WEPP)	Ascough et al. 1997; http://www.ars.usda.gov/Research/docs.htm?docid=10621	Simulation model of water erosion (infiltration, runoff, raindrop and flow detachment, sediment transport, deposition, residue decomposition)	Parameterized for many US soils; can generate long-term, daily climatic data from more than 2 600 US weather stations; Web-based user interface	Does not simulate livestock movement among different forage types, patches, or pastures

herbivore movements in response to forage parameters. Rangeland models can also be linked with predictive forecasting of precipitation in a spatially explicit manner through GIS. For example, the forage and livestock production models in Great Plains Framework for Agricultural Resource Management (GPFARM; Andales et al. 2005, 2006) could be directly linked with the National Weather Service's Climate Prediction Center for 6–10-d, 1-mo, and 3-mo outlooks[1] for forage projections and associated probabilities of risk for specific periods of management interest to land managers and livestock producers. These forage projections could be spatially explicit and tied to existing soils maps and/or developing ecological site descriptions through state-and-transition models (see below). This information could be used to more closely match forage demand and availability in an uncertain and changing environment (Popp et al. 2009) and to increase profitability through adaptive management involving flexible stocking (Ritten et al. 2010; Torell et al. 2010). Finally, rangeland model simulations could be performed in real time via Web-accessible portals to increase utility for rangeland management. Although it does not use real-time data, RHEM is available as a user-friendly, Web-based tool[2] and represents erosion processes under disturbed and undisturbed rangeland conditions. Model hydrologic and erosion parameters are dynamically linked with rangeland plant communities through a new system of parameter-estimation equations based on 204 plots at 49 rangeland sites distributed across 15 western US states (Nearing et al. 2011).

Another important challenge is better integration of remote-sensing methods with mechanistic rangeland models to provide decision makers with improved decision support tools for spatiotemporal rangeland assessment and monitoring. The use of remotely sensed data in rangeland models has been limited in the past (Hunt et al. 2003); nonetheless, the potential exists for remote sensing to provide information on many of the parameters and variables (e.g., soil, hydrology, vegetation) required by rangeland simulation models. For example, at the Walnut Gulch Experimental Watershed in southeastern Arizona, high-spatial, low-temporal scale, visible remote-sensing data were used to calibrate a rangeland ecosystem model for semiarid, perennial grasslands (Nouvellon et al. 2000, 2001). Nouvellon et al. (2001) theorized that a coupled remote-sensing modeling approach could provide spatially distributed information about both vegetation and soil conditions for day-to-day management and decision making. Other decision support tools, including livestock early warning systems, such as the Livestock Information Network and Knowledge System (LINKS, Kaitho et al. 2007), combine remote-sensing, field data, and simulation modeling to provide current and near-term projections of forage to assist in stocking decisions associated with adaptive management (Angerer et al. 2008). Unfortunately, adoption of these emerging forecasting and decision support tools by land managers remains an obstacle because of social and institutional barriers (Matthews et al. 2008; Marshall et al. 2011).

With likely greater variability in precipitation expected with emergent global climate change, optimizing grazing and other management practices in rangelands, especially in arid and semiarid environments, presents additional challenges for increasing the utility of models for rangeland management (Baker et al. 1993; Quaas and Baumgartner 2012). Tietjen and Jeltsch (2007) reviewed 41 models published between 1995 and 2005 for simulating arid and semiarid livestock grazing systems and also evaluated model potential to simulate climate change effects. They found there was a clear need for rangeland models to better simulate the effects of climate change (especially to be efficacious as decision support tools for managers), with critical shortcomings including ignoring the effect of increased atmospheric CO_2 levels on the ecosystem (e.g., plant productivity) and the inability to account for changing precipitation patterns. The consideration of both of these external drivers is crucial under climate change; hence, sustainable, long-term decision making for rangelands is currently lacking important information (Tietjen and Jeltsch 2007).

CONTEMPORARY MODELING NEEDS

Inherent spatial and temporal variability in biophysical factors (e.g., soils, plant communities, animals, and precipitation) necessitates that modeling, in theory at least, be a basis for extrapolating ecological information from short-term experiments and research locations to landscapes in differing environments (e.g., Andales et al. 2005, 2006). Establishment of new networks, such as the Long-Term Agro-Ecosystem Research (LTAR[3]) network for agriculture (Walbridge and Shafer 2011), offer promising frameworks for robust, spatially explicit, on-the-ground data for model parameterization (current weaknesses identified in Table 1), validation, and improvement, as well as multiscale (pasture to watershed to landscape to continental) synthesis efforts. Using models for rangeland management decision making at the enterprise level requires that three other elements be included, in addition to biophysical factors: 1) a fundamental understanding of the historic drivers (e.g., grazing, fire) and spatiotemporal variation in their effects on the landscape (see Table 1, SAVANNA model); 2) manager capacity, including experience, skills, and availability; and 3) changing constraints of the enterprise (e.g., ranch), which commonly pertain to economics (Budd and Thorpe 2009). Land managers need these elements incorporated to evaluate multiple management strategies involving interacting drivers, to determine risk assessments and economic outcomes, and the flexibility to address the changing aspects of individual enterprises. Furthermore, contemporary themes regarding ecosystem services and management objectives, such as the use of livestock as “ecosystem engineers” (Derner et al. 2009) to manipulate vegetation at multiple scales (e.g., Toombs et al. 2010), need to be addressed and oblige modelers to assess multiple and potentially competing ecosystem goods and services as outputs from models.

As previously discussed, current rangeland models have considerably increased our fundamental knowledge and understanding of the dynamics of ecosystem functions, processes, and structure (Table 1). However, most, if not all, of these models are monolithic (i.e., the code has been developed in a

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[1] http://www.cpc.ncep.noaa.gov.

[2] http://dss.tucson.ars.ag.gov/rhem/.

[3] http://www.ars.usda.gov/ltar/.

"block" structure with tight coupling between submodels) and is thus not modular. A major disadvantage of building monolithic simulation models is that conceptual boundaries within the model are not captured correctly or there is simply no separation between concepts in the code. Furthermore, code modifications (e.g., changes in process representation) in monolithic models typically require considerable time, effort, and expense (Ahuja et al. 2005). One highly promising area for advancing the development and delivery of rangeland models is the use of component-based modeling techniques within a modeling framework environment. A modeling framework can provide support for rangeland models by expediting the disaggregation of modeling functions into well-structured components (i.e., modules, subroutines, or submodels). Components, once implemented in a particular framework, are able to be reused in other models coded to the same framework with very little migration effort. One advantage of using a common modeling framework is that preexisting modules or components may exist in a digital library that can help facilitate model development (Argent et al. 2006). The Object Modeling System Version 3 (OMS3; Ahuja et al. 2005; David et al. 2010) is a modeling framework that is well suited for development, data provisioning, validation, and application of rangeland models. The OMS was first released in 2004, and Version 3.0 represents a major milestone toward an easier to use framework implementation. The OMS3 provides an unprecedented capacity to develop models and decision support tools using components (e.g., biophysical, ecological, economic, and climatic) from a digital library, and facilitates "customized modeling," in which the developed model can be fit to a specific problem and customer need. For rangeland systems, the OMS3 has the capacity to advance initial efforts that linked submodels of hydrology and forage production (Pierson et al. 2001) and can be used to rapidly create models by combining components representing important rangeland processes (e.g., hydrology, erosion, vegetation, livestock, management, etc.). As modules are updated and new advancements in science incorporated, these components can be inserted into existing models in a "plug-and-play" effort. In summary, adoption of component-based modeling techniques and use of a modeling framework, such as the OMS3, can help advance rangeland model development by

1) Making rangeland models much easier to build, access, understand, and use;
2) Reducing duplication of development efforts and improving the quality of rangeland model code;
3) Facilitating long-term maintainability of existing and new rangeland models;
4) Promoting greater consistency of rangeland modeling for different scales and spatiotemporal problems; and
5) Improving response and delivery times in rangeland modeling projects.

INTEGRATING NEW EXPERIMENTAL AND EXPERIENTIAL KNOWLEDGE INTO MODELS

Linking science, monitoring, and management has long been a fundamental staple of the Society for Range Management and for resource managers in many disciplines (Biggs and Rogers 2003; Gillson and Duffin 2007). Unfortunately, there are often major disconnects between management and science knowledge sources, as exemplified in the persistence of the rotational grazing debate (Briske et al. 2008, 2011). Incorporating human dimensions of land managers, such as perceptions, knowledge, and enterprise-level decision-making processes, and associated variability regarding the commitment, ability, goals, and opportunities of land managers is also needed (Briske et al. 2011). There remains an underappreciation that social and economic processes are as important as ecological processes for rangeland management (Lynam and Stafford Smith 2004) and that land managers are capable of learning from and adapting to changing circumstances (Stafford Smith et al. 2007) to make effective management decisions to capture opportunities and avert hazards (Briske et al. 2008, 2011; Brunson and Burritt 2009; Rigueiro-Rodríguez et al. 2011).

One promising framework for integrating experimental and experiential knowledge, including observations, along with monitoring for decision making and adaptive management, is the ecological site description that incorporates state-and-transition models (Bestelmeyer et al. 2009; Rumpff et al. 2011). Ecological sites are distinguished by soil properties and processes (Duniway et al. 2010), which facilitates use of existing spatially explicit soil maps. State-and-transition models within the ecological sites are diagram depictions and associated narrative text descriptions of the vegetation and soil dynamics (Westoby et al. 1989), which can be used to apply adaptive management (e.g., Knapp and Fernandez-Gimenez 2009). When modelers add desired outcomes from land managers to state-and-transition models, it provides greater focus and relevant output for informed decision making and facilitates adaptive management, which could incorporate predictive forecasting and integrated, experimental and experiential knowledge within the context of climatic variability (Fig. 1). Adaptive management, informed by feedback from models, can be applied to shift between states or to maintain states through decision criteria that use livestock movement and grazing strategies to influence livestock foraging decisions.

We view ecological site descriptions and associated state-and-transition models as a way of representing the plant- and soil-based components of complex simulation models in a more simplistic manner that increases utility for end users but still captures the essential biophysical factors generating spatial variability in rangelands. This offers the opportunity to better match model complexity with ranch decision-making goals. Sophisticated ecosystem models (e.g., SAVANNA, SPUR) often have more complexity than is needed for decision making by individual land managers (Weisberg et al. 2006). State-and-transition model frameworks of ecological site descriptions simplify plant growth and dynamics relative to the topoedaphic variability, incorporate indicators of ecosystem function (Kachergis et al. 2011), respond to environmental change (Phillips 2011), and capture herbivore feedbacks to plant dynamics associated with livestock management through grazing-induced vegetation change thresholds (e.g., Sasaki et al. 2008, Fig. 1). Recognition that vegetation responses to grazing can be nonlinear can assist land managers in preventing the occurrence of undesirable states and promoting desirable

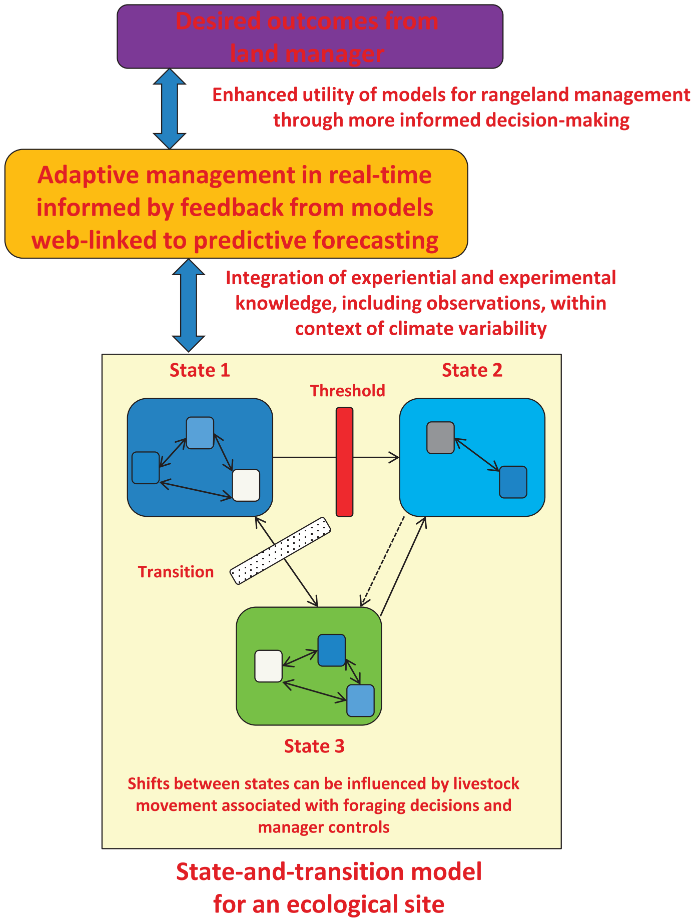

Figure 1. Framework for enhancing utility of models for rangeland management through more-informed decision making and adaptive management by incorporating both experimental and experiential knowledge, including observations, within an ecological site context.

states with appropriate grazing management practices (Sasaki et al. 2008).

To increase the utility of the state-and-transition modeling framework, an important component is incorporating spatial aspects of livestock foraging behavior. A critical advance would be the ability to assess livestock movements and management decisions within landscapes containing multiple ecological sites, states, and pasture configurations for their effects on both livestock production and potential future transitions between states. In their current form, ecological site descriptions essentially treat sites as being independent with regard to herbivore movements. The “rules” that many models have used to simulate herbivore foraging decisions, and hence, movements among patches of varying forage quality (e.g., Moen et al. 1998; Christensen et al. 2003; Plumb et al. 2009), can provide guidance to the development of decision support tools based on characteristics of individual ecological sites that effectively incorporate livestock movement. An important consideration is the way in which short-term rates of forage intake by livestock are linked to daily and seasonal consumption rates in a spatial context (Weisberg et al. 2006), which ultimately influences longer-term shifts in plant community composition and potential transitions among ecological states. The explicit influence of water and fencing distribution on foraging decisions will need to be incorporated to achieve utility for end users.

A second key opportunity for increasing utility of the state-and-transition modeling framework is incorporating how social and economic factors as well as human capacity influence decisions by land managers (Fox et al. 2009; Reid et al. 2009; Fazey et al. 2010). It is encouraging that integration of experiential knowledge into state-and-transition models is already occurring (Knapp and Fernandez-Gimenez 2009; Knapp et al. 2011). Combining Bayesian network dynamics (a representation of probabilistic relationships among variables of interest) into state-and-transition models can assist land managers in understanding the probability of transitioning between states (e.g., Rumpff et al. 2011). For example, although the state-and-transition model may depict that state 1 can transition to state 3 (Fig. 1) and vice versa, knowledge about the probability of that occurring would benefit land managers. If state 3 was less desirable than state 1 for a land manager and the probability of moving from state 1 to state 3 was high but the probability of moving back from state 3 to state 1 was low, then management decisions could be made to ensure that state 1 was maintained. Conversely, for vegetation already in state 3, allocating finite resources or changing management to attempt to transition to state 1 would be less desirable. Bayesian networks, therefore, function to increase the communication for state-and-transition models among researchers, land managers, the general public, and policy makers, as well as updating those models with new data, both experimental and experiential (Bashari et al. 2008; Nicholson and Flores 2011; Rumpff et al. 2011).

MANAGEMENT IMPLICATIONS

Increasing the utility of models for rangeland management remains an important frontier research priority for the modeling community because models are still rarely used to assist land managers with decision making. Improvements needed include involving decision makers in model development, increasing communication between scientists and managers, reducing the complexity and computational requirements of models, and consistent terminology (Silvert 1989; Bunnell and Boyland 2003; Weisberg et al. 2006; Schmolke et al. 2010). Advances may be achieved less by further model complexity and more by the use of modeling approaches that 1) use component-based, code-development techniques for increased model modularization; 2) facilitate rapid parameterization of models for new ecosystems and individual enterprises based on existing databases; 3) allow users to incorporate new experimental and experiential knowledge; and 4) facilitate outcome-based, adaptive decision making at the enterprise level based on ecological and economic considerations. Development and refinement of models need to be cognizant of 1) increasing user friendliness and Web-portal accessibility for individual enterprises, 2) providing realistic outputs and information for decision making from inputs that balance complexity and simplicity (e.g., Bunnell and Boyland 2003; Weisberg et al. 2006), and 3) providing an appropriate level of training for the end user to quickly become comfortable with the use and possibilities of the model for enhanced proficiency. Opportunities exist for increasing the utility of models for decision making and adaptive rangeland management by incorporating a fundamental understanding of the historic drivers (e.g., grazing, fire) and spatiotemporal variation and their effects on multiple ecosystem functions to facilitate 1) landscape-level decision making for multiple ecosystem goods and services with consideration of economics and sustainability (Nelson and Robinson 2009; Guan et al. 2011) and 2) determinations of spatially explicit locations for application of conservation practices (comparing costs and benefits accrued across different timescales) to optimize desired outcomes while efficiently using economic inputs (Goodrich et al. 2011). Models must be sufficiently flexible to incorporate new experimental and experiential knowledge and the manager's experience and skill sets (Knapp et al. 2011). To this end, providing managers and other stakeholders the opportunity to contribute to, and challenge, model assumptions before the development process is complete will help to create a sense of ownership in the model and increase the likelihood that the model will be used. Finally, useful models should be capable of forecasting effects of a changing and variable climate, including the directionality, magnitude, and uncertainty of those changes on enterprise-level risk (Freier et al. 2011).

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