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Original Research

Using State and Transition Models to Show Economic Interdependence of Ecological Sites at the Ranch Level

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ABSTRACT

US government agencies are adopting state and transition models (STMs) for rangeland evaluation, monitoring, and management. This research demonstrates advantages of combining STMs and ranch economic models. A dynamic optimization framework casts management decisions—stocking rates and brush control—in the context of ranch profitability over a suite of ecological sites. Markov processes characterize the likelihood of state transitions.
The ranch model shows economic interdependence of multiple ecological sites. Ecological site combinations producing the most forage are not the most economically advantageous. The state of one ecological site influences the forage value elsewhere and ultimately the intensity at which a ranch is stocked. Likewise, brush control benefits depend importantly on the state of all ecological sites.
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Introduction

Rangelands in the western United States are complex socioecological systems. Scientists are gaining a better understanding of the complexity, and recommendations for natural resource management policies are evolving as a result. Among recent changes is a transition away from "command and control"[1] management and equilibrium-oriented scientific paradigms (Holling and Meffe, 1996) in favor of land stewardship that applies adaptive management and collaborative learning in order to build ecological and social resilience (Walker et al., 2002; Berkes et al., 2003; Olsson et al., 2004; Pahl-Wostl and Hare, 2004; Keen et al., 2005; Walker and Salt, 2006). Pursuant to a growing focus on adaptive management, the US Department of Agriculture Natural Resource Conservation Service (NRCS), US Forest Service (FS), and Bureau of Land Management (BLM) signed a 2010 memorandum of understanding (USDA, 2010) agreeing to adopt state and transition models (STMs) as a standard basis for rangeland inventory and monitoring. STMs represent a key tool in the process of adaptive management because they provide a clear representation of the best current knowledge about how an ecosystem responds to different management and environmental factors. STMs are used to assess current rangeland conditions in relation to known ecosystem dynamics, identify management objectives, select appropriate monitoring indicators, and assess whether objectives are being met (Bestelmeyer et al., 2003, 2004).

The objectives for this research are to extend the understanding and application of STMs by 1) creating a coupled STM-economic model that examines important ecosystem service trade-offs and the path dependency of management decisions; 2) scale the coupled STM-economic model to a land management unit representative of ranch decision making; 3) demonstrate the utility of the STM-economic model in a specific application to the Elkhead watershed in north-central Colorado.

STMs provide significant advantages over previous linear, succession-based models because they incorporate nonlinear, dynamic ecological processes and also represent linear dynamics where they occur. The major objective for this research is to create a coupled economic-STM that considers how land management decisions influence the provision of forage production for cattle amidst stochastic weather and fire events.

STMs have been published for a number of vegetation types (Westoby et al., 1989; Bestelmeyer et al., 2003; Wilkinson et al., 2005) on the basis of quantitative analysis of field data (Scanlan, 1994; Allen-Diaz and Bartolome, 1998; Stringham et al., 2001), quantitative analysis of qualitative expert knowledge (Plant et al., 1999; Plant and Vayssieres, 2000), and quantitative analysis of qualitative data (Bellamy and Brown, 1994; Bestelmeyer et al., 2003, 2004). While

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[1] "Command and control" models of resource management typically aim to limit variation of natural systems in order to provide a predictable supply of specific ecosystem good(s) or service(s), but they often have the result of limiting resiliency.

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STMs are useful in describing complex ecological systems, they often do not provide land managers with adequate information to make optimal management decisions (Bestelmeyer et al., 2003), and in particular economic and financial measures of benefits and costs of management decisions are lacking. Coupling economic information with STMs provides one opportunity to further enhance the utility of these models.

As with ecological models, economic models of ranching operations have evolved over time. Early ranch economic modeling assessed the profitability of range improvements with static net present value analysis. Forage availability is forecast over selected managerial time horizons, which then leads to a forecast of annual cash flows based on whole ranch budgets. These future cash flows are discounted to the present and investment criteria applied (Workman, 1986). Later economic modeling sought to relax the deterministic approach to forage productivity and allow for stochastic disturbances (e.g., weather). Bernardo (1989) applies a Markov chain modeling approach for selecting range improvement strategies along with other practices. Likewise, Frasier and Pfeiffer (1994) use a Markovian decision analysis to identify optimal beef cow management. Both of these articles consider forage production to be a dynamic variable subject to uncertainty that is characterized by Markov chains. Ritten et al. (2010) extend dynamic modeling of rangelands to characterize forage production with weather variability and initial rangeland productivity. The authors employ an infinite time horizon within the empirical application. The model illustrates how variable weather impacts optimal stocking decisions, but the successional nature of the model precludes adaptive management opportunities that might be found in an STM.

Epanchin-Niell et al. (2009) use an STM approach to examine optimal postfire restoration strategies. They adopt the STM perspective when evaluating natural disturbances and anthropogenic changes that increase the occurrence of cheatgrass *(Bromus tectorum)* monocultures in the Great Basin sagebrush steppe. The STM framework is chosen because it incorporates livestock grazing, weather, and fire as disturbances that influence the likelihood of transitioning between vegetation states. The authors appreciate the advantages of STMs but note that limited knowledge of transitions make STMs difficult to apply directly. The authors also limit their effort to a 50-yr time horizon making long-term analysis of potential transitions difficult.

Kobayashi et al. (2014) use the STM framework to determine optimal stocking and weed control strategies for a ranch consisting of a single ecological site, which can be in three different states, with one of two transitions being irreversible. They find that current state influences both treatment and stocking decisions, with treatment only being beneficial as a prevention measure when the site is in the most productive state. Their model reflects a situation in which a state is already compromised by an annual invasive grass (cheatgrass). Therefore, their model "will transition over time to the annual grass-dominated state even without disturbance such as wildfire or excessive livestock grazing" (pg. 626). Their model also ignores the impact of variable weather on both forage production and the likelihood of transitions.

The previous literature is foundational for this research in that STMs are used to understand ecological state transitions within an ecological site, and a Markov approach is often used to characterize the transitions. We also scale STMs to a land management unit, a representative ranch composed of three distinct ecological sites, and include ranch economic decisions within a dynamic optimization framework. More specifically, a coupled model is used in which a ranch manager's previous stocking rate influences the current ecological state and subsequent provision of forage production. Current management decisions (stocking and brush control) are made conditionally on existing states, and stochastic weather and fire events influence the likelihood of transition to other states in the next period. The current state directly influences the optimal stocking rate and decision to spray. The existing herd size and calf sale revenues impact the ability to invest and benefit from range improvements such as brush control.

Methods

Study Area

The analytical framework and empirical approach is focused on Moffat and Routt counties in northwestern Colorado. These counties include nearly 2 million ha of diverse rangelands and forested mountains. Ranching remains the dominant land use in Moffat County, and ranches comprise 59% of the private land in Routt County. According to the Census of Agriculture (2009), over 85% of the ranches in Routt County are involved in beef cow/calf production systems. The geographic area of this model includes high-elevation parklands, sagebrush grassland, and oak shrublands, as well as semidesert shrublands. The focal point of this study is the 60,000-ha Elkhead watershed. The Elkhead watershed is mapped as Major Land Resource Area 48A Southern Rocky Mountains and borders on 34A Cool Desertic Basins and Plateaus. As such, the ecological sites in this area of Colorado resemble those in Wyoming and Utah, as well as the broader Intermountain West region.

Ecological Site Descriptions

The STMs used in this analysis are from integrated models created with qualitative local knowledge and quantitative ecological field data (Kachergis, 2011; Knapp et al., 2011; Kachergis et al., 2013). The STMs include three ecological sites prevalent in the Elkhead watershed: Claypan, Aspen, and Mountain Loam. The representative ranch model contains the same percent of the three ecological sites as the watershed as a whole.

Table 1 defines the states present in the ecological sites, and graphical representations for the STMs for Claypan and Mountain Loam Sites can be seen in Figures 1 and 2, respectively. The Claypan site has four states labeled C1 through C4, Aspen has two states labeled A1 and A2, while Mountain Loam has three states labeled L1 through L3. Kachergis (2011) gives a detailed explanation of the states, but differences in soil type, vegetation, plant cover, and species composition mean that each state differs in its provision of ecosystem services, which may give rise to differing management approaches. For example, L1 and C1 have a greater cover and higher diversity of understory plant species compared with other states. These two states also contain granular soil structure, higher organic matter content, and no invasive species, findings consistent with other descriptions of reference states for sagebrush steppe (USDA-NRCS, 2003; Crawford et al., 2004; Kachergis et al., 2012). These states may allow different economically optimal stocking rates or other managerial decisions as compared with L2 and C3, which have the highest shrub cover, lowest grass and forb cover, and lowest production potential for their ecological sites (Kachergis et al., 2012).

Despite many similar state properties, ecological transitions differ between the ecological sites. Transitions are shifts between states that occur when the ecological processes maintaining the state are disrupted, causing self-reinforcing positive feedbacks (Briske et al., 2006). Major feedback mechanisms in semiarid rangelands include

Table 1
Description of ecological sites and states

	Claypan
C1	Diverse and alkali sagebrush/bluegrass shrubland
C2	Native grassland
C3	Eroding alkali sagebrush shrubland
C4	Alkali sagebrush/western wheatgrass shrubland
	Aspen
A1	Tall forb understory
A2	Shrubby understory
	Mountain loam
L1	Mountain big sagebrush shrubland with diverse understory
L2	Dense mountain big sagebrush shrubland
L3	Mountain big sagebrush/western wheatgrass shrubland

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