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Original research article

Linking ecosystem services with state-and-transition models to evaluate rangeland management decisions☆

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HIGHLIGHTS

- We simplified the existing state-and-transition models for rangelands using remote sensing technologies over larger landscapes.
- We developed an optimization model to include ecosystem services and dis-services in the state-and-transition models.
- Linear programming optimization model was run for private and public ranchers.
- Net benefit was maximum for the public rancher when ecosystem disservices were excluded.
- Rangeland managers can use the optimization model to compare different management alternatives.

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1. Introduction

Ecosystem services are defined as the components of nature that are directly enjoyed, consumed, or used to produce specific, measurable human benefits (Escobedo et al., 2011). The Millennium Ecosystem Assessment has introduced widely the concept of ecosystem services and proper management of these attributes (MEA, 2005). Along with the services, ecosystems also provide dis-services that affect well-being by reducing productivity and increasing production costs (Escobedo et al., 2011; Lyytimäki and Sipilä, 2009; Zhang et al., 2007). The net ecosystem services, i.e. positive services minus negative services (dis-services), affect the well-being of an ecosystem thereby impacting its health.

Rangelands occupy a major portion of world's land but are often under-appreciated because they are less significant than croplands in terms of primary productivity. Management activities make changes in the ecological conditions of the area in addition to vegetation communities and other physical characteristics. Net ecosystem services include all marketed and non-marketed benefits, and costs from a unit of land. These services include all tangible and intangible costs, and benefits that humans get from ecosystems. Quantifying these goods and services is a crucial topic for protecting ecosystem services and land management decision making (Costanza et al., 1997; De Groot et al., 2002; Farber et al., 2002; Howarth and Farber, 2002; Sagoff, 2011). However, conventional markets and market prices are usually not able to capture the opportunity costs

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of using natural resources (Costanza et al., 2014), for example accelerated erosion could reduce future production onsite and lead to sedimentation problems downstream, but those costs would be difficult to quantify in a metric comparable to the price of calves. Hence, studying ecosystem services and dis-services as a measure for tradeoffs of management costs and benefits in a particular area can aid in making efficient management decisions.

Ecosystem services from rangelands are even less well-understood since rangelands are themselves extensive, complex, and sometimes underrated ecosystems (Havstad et al., 2007; MacLeod and Brown, 2014). Those ecosystem services do not pass through a market for valuation, though the cost would often be very high, if through mismanagement, the ecosystem is no longer capable of providing those services. Estimates of the values of ecosystem services are potentially measurable variables for understanding ecosystem dynamics, health and integrity, and thus, sustainable land management decision making (Brookshire et al., 2010; Reed et al., 2015). Public land management agencies and also private lands spend a major portion of their annual budget in conservation programs with a primary goal to conserve biodiversity and to protect or restore ecosystem services (Briske, 2011). But economically efficient investments require proper assessments. For both economic decision making and establishing management priorities in changing environment, the test of economic efficiency is: does the cost of transitioning from one state to another exceed the benefits expected by increases in the flows of ecosystem services?

In the West, much of the land, and hence much rangeland, is publicly owned, with 47% of the land in the 11 coterminous western states owned by the federal government. The Federal Land Policy and Management Act of 1976 serves as the "organic act" gives the Bureau of Land Management its multiple use mandate, which includes the goal of:

> *harmonious and coordinated management of the various resources without permanent impairment of the productivity of the land and the quality of the environment with consideration being given to the relative values of the resources and not necessarily to the combination of uses that will give the greatest economic return or the greatest unit output.* (http://www.blm.gov/flpma/FLPMA.pdf, *page* 2).

In other words, Congress has given the BLM the power to make decisions that value natural systems over purely economic values. The first objective of this paper is to demonstrate how a framework for consideration of the economic tradeoffs could work for rangelands. The paper does not solve all the problems associated with the approach, which would require a larger effort, but clearly there is a need for explicit consideration of the "relative values" of the resources. The tools for understanding tradeoffs of relative values are economic tools, specifically those from constrained optimization which provide shadow prices, relating to the additional value in the objective function related to relaxing a constraint. Optimization is required if we want to provide the public with the most of what it wants from its resources, though what it wants may be defined locally, with public input. Here we use the simplest tool for constrained optimization, linear programming. Linear programming (also known as linear optimization) is an applied mathematical model for maximizing benefits or minimizing costs for a set of variables under a finite number of constraints (Chvatal, 1983).

This study focuses on using net ecosystem services as a framework for rangeland watershed management. The second major objective of this research is to build on the state-and-transition model (STM) concept as a base to understand ecosystem dynamics in public rangelands in the West, and to help land managers and ranchers improve their management decisions through understanding the tradeoffs of states based on the flows of ecosystem services. Congress directed the Secretaries of the Interior and Agriculture to work together to develop a standard ecological classification system. An interagency handbook was published in 2013 describing the system, including development of state and transitions models. (http://directives.sc.egov.usda.gov/OpenNonWebContent.aspx?content=33151.wba). This study addresses the issue of emphasizing state and transition models as an important framework to understand the vegetation dynamics in rangelands and of exploring the role of ecosystem services in land management decision making. A research method used for this study was the linear optimization model, which uses ecosystem services to analyze investments on conservation and management activities. Rangeland managers can use such a model to understand and explain, not prescribe the tradeoffs of management investments. State-and-transition models gives managers additional information to make better decisions, yet require more research and monitoring for application across many ecological sites.

2. Relating ecosystem services with STMs in rangelands

STMs are a powerful conceptual framework, developed by the United States Department of Agriculture-Natural Resources Conservation Service (USDA-NRCS) for each ecological site, for management of rangelands through defining potential vegetation communities, describing the management induced transition of one vegetation community to another, and documenting the expected benefits provided by the various potential vegetation communities (Bestelmeyer et al., 2003, 2010, 2011; Briske et al., 2006; Herrick et al., 2006; Knapp and Fernandez-Gimenez, 2009; Knapp et al., 2011; Stringham et al., 2003). These models are effective as tools for communicating ideas about vegetation changes and decision making in rangelands (Bestelmeyer et al., 2009; Briske et al., 2005).

The Natural Resources Conservation Services (NRCS) has developed a STM for each ecological site in southern Arizona. The STMs can be found at the Ecological Site Descriptions (ESDs) website (https://esis.sc.egov.usda.gov/Welcome/