A Tool for Projecting Rangeland Vegetation Response to Management and Climate

By Paulette L. Ford, Matthew C. Reeves, and Leonardo Frid

On the Ground

- New technologies may enhance management by enabling quantitative testing of assumptions of vegetation response to climate and management. State-and-transition simulation models can keep track of interactions that are too complicated for us to comprehend using only conceptual models.
- This tool takes conceptual state-and-transition models to the next level, fostering greater communication and dialogue with stakeholders. Based on the models and climate data used here, increased drought may enhance transitions between vegetative states.
- It is important to be as explicit and quantitative as possible as to how you expect vegetation states or ecosystem processes to transition between one another.

Keywords: state-and-transition simulation models, climate change, drought, semi-arid ecosystems, grazing, fire.

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Introduction

There are a number of complex and intractable problems facing rangeland managers attempting to promote the sustainable use of semiarid ecosystems in the Southwestern United States. These challenges include such issues as invasions by exotic species, the expansion of woody vegetation, altered fire regimes, and drought.[1] Compounding these issues is the added uncertainty about how these problems will respond to a changing climate.[2] Despite these problems and uncertainties, land managers and producers must make decisions today that will likely have an impact on landscapes decades into the future. Therefore, tools are needed that allow us to visualize the possible future outcomes of today's actions. These should be helpful in identifying uncertainties in our understanding of rangeland landscapes and trade-offs associated with alternative management actions.

Conceptual state-and-transition models (STMs),[3] such as the ones included in ecological site descriptions,[4] are tools that allow managers to describe the possible vegetation communities that can occur on a particular ecological stratum (i.e., ecological site) and identify the drivers of change that can shift vegetation composition and productivity. Drivers of change can be either natural processes, such as wildfire or drought, or anthropogenic ones such as herbicide application or prescribed fire. State-and-transition models are useful in identifying thresholds between vegetation states, designing monitoring and management programs, and developing a landscape classification system.[4,5] However, STMs are limited in their use for making quantitative projections of what a future landscape might look like under different "what-if" scenarios.[6,7] In addition, when using STMs, it is difficult to account for interactions that can occur between the various transitions, stressors, and pathways noted in the models. This issue becomes even more pronounced when considering future climate patterns.

One tool that helps make sense of these complicated factors acting simultaneously are State-and-transition simulation models (STSMs).[8] STSMs are known for their ability to explore the combined effects of multiple disturbances, ecological dynamics, and management actions on vegetation. However, integrating the additional impacts of climate change into STSMs remains a challenge.[9]

STSMs extend conceptual STMs by quantifying the rates at which transitions occur under different circumstances. These rates can be specified as probabilities at each model timestep and can be further refined to accommodate complex interactions such as age dependence and area or cost targets for management activities. To make the STSM tool spatially explicit, landscapes are usually divided into simulation cells. Next, their starting state class, possible transition pathways, and probabilities are estimated. State classes represent the different discrete classes of vegetation communities that can occur on each simulation cell. Transition pathways can be thought of as the direction that vegetation moves in response to stressors or management actions (e.g., what is the likely outcome of repeated drought on a given site). Once pathways have been developed, probabilities quantified, and landscapes divided into cells, STSMs can be used to project vegetation response under different “what-if” scenarios and can include estimates of the range of uncertainty associated with future projections.[8]

For this project we demonstrate how STSMs can be used as a tool to make projections of landscape change under different climate and grazing scenarios for semiarid ecosystems in the New Mexico Rocky Mountain Region. We use a suite of pre-existing STSMs developed as part of the Integrated Landscape Assessment Project (ILAP)[10] and apply them to different climate and grazing scenarios.

The goal of this study is to demonstrate use of this modelling approach to help understand effects of climate and management regimes on vegetation composition, annual production of vegetation, and sustainability of cattle grazing. In addition to aiding our understanding of potential impacts, this tool also enables managers and producers alike to determine if their assumptions about the response of vegetation to climate and herbivory in their domain are valid or need to be revaluated. Finally, we demonstrate how this tool enables identification of incorrect assumptions about vegetation dynamics, therefore suggesting that correct implementation of the modelling approach requires an iterative process.

Methods

Study Area

The study area for this project is the portion of the ILAP New Mexico Rocky Mountains (NRM) region that consists of nonforested potential vegetation types (PVTs). Here PVTs represent a kind of physical and biological environment that produces a distinctive kind of vegetation. These PVTs were created and defined during the ILAP process by numerous ecologists, planners, nonprofits, wildlife biologists, range managers, and academic professionals from Oregon State University and Arizona State University. We obtained a spatially explicit dataset from the ILAP project (https://ecoshare.info/ilap/about-ilap/). This region represents an area of just under 10 million acres and encompasses 18 different PVTs (Fig. 1; Table 1). The most prominent PVT on the landscape is Shortgrass Steppe – Juniper Potential with over 3 million acres. Two other PVTs (Colorado Plateau / Great Basin Grassland – Juniper Potential and Sagebrush Shrubland) are prominent with over 1 million acres each. All other PVTs represent well below a million acres each on the landscape. The state classes for each PVT in an STSM represent a discrete set of the possible vegetation communities that can occur on that PVT. Each PVT has between 4 and 19 state classes defined with a total of 177 state classes across all PVTs. In the ILAP semiarid models for the NRM region, state classes are defined based on dominant vegetation cover and the density of three vegetation life forms: grass, shrubs, and trees.[10] Ranching operations and use of federally managed grazing allotments are common throughout this area. Note that our simulations included all PVTs but we focus our analysis of the model results on only the three most prominent ones listed above. (See Pictures 1–3.)

Integrated Landscape Assessment Project State-and-Transition Simulation Models

STSMs developed for the NRM region were obtained from the ILAP project authors.[10] A critical aspect of STSMs that must be considered is the likelihood of transition to other vegetation classes resulting from a climatic or managerial forcing. Documentation justifying differences in transition probabilities for grazing and drought, two major drivers of change in the ILAP models for this region, is limited. Differences in probabilities for grazing could be due to either differences in grazing preference or the likelihood of vegetation response. Regarding drought probabilities, differences could be due to different climates in each PVT or the likelihood of a response in vegetation when drought conditions occur. It is particularly unclear whether differences in probabilities between different PVTs and state classes are meaningful or the result of models being developed by different experts. To simplify assumptions about drought and grazing we made probabilities of vegetation change to livestock grazing and drought to be a function of productivity (see sections on Drought and Grazing below). This represents a first approximation, which can be iteratively revised using published literature, model calibration, expert knowledge, etc. Other transitions simulated in the model include exotic invasion, fire (surface, mixed, and stand replacing), and juniper and shrub invasion. We focus our analysis on grazing and drought as the most prominent transitions on the landscape. The full suites of model inputs are available as a SyncroSim model library in the supplementary materials (http://syncrosim.com/index.php?title=SyncroSim). The model was spatially explicit and simulated at a 200m resolution. The extent of the landscape is 9,954,032 acres (1,007,065 cells). We ran the model from the year 2000 to 2099 at an annual resolution.

Model Scenarios

STSM scenarios can include numerous management options, climatic extremes, and other perturbations to the ecosystem. We wanted to examine the effects of climate (including drought) and grazing. However, we did not want to create new STSMs, but instead focus on models already in use by land managers to demonstrate the utility and process of using this tool to help quantify vegetation dynamics. To estimate the effects of these perturbations and their potential interactions, it is necessary to quantify the probability that each action will influence vegetation composition and function.

In the present case study, we simulated 10 climate scenarios encompassing six Global Circulation Models (GCMs) and two representative concentration pathways (RCPs; Table 2) using spatially downscaled data[11] rather than raw GCM data. RCPs are greenhouse gas concentration trajectories

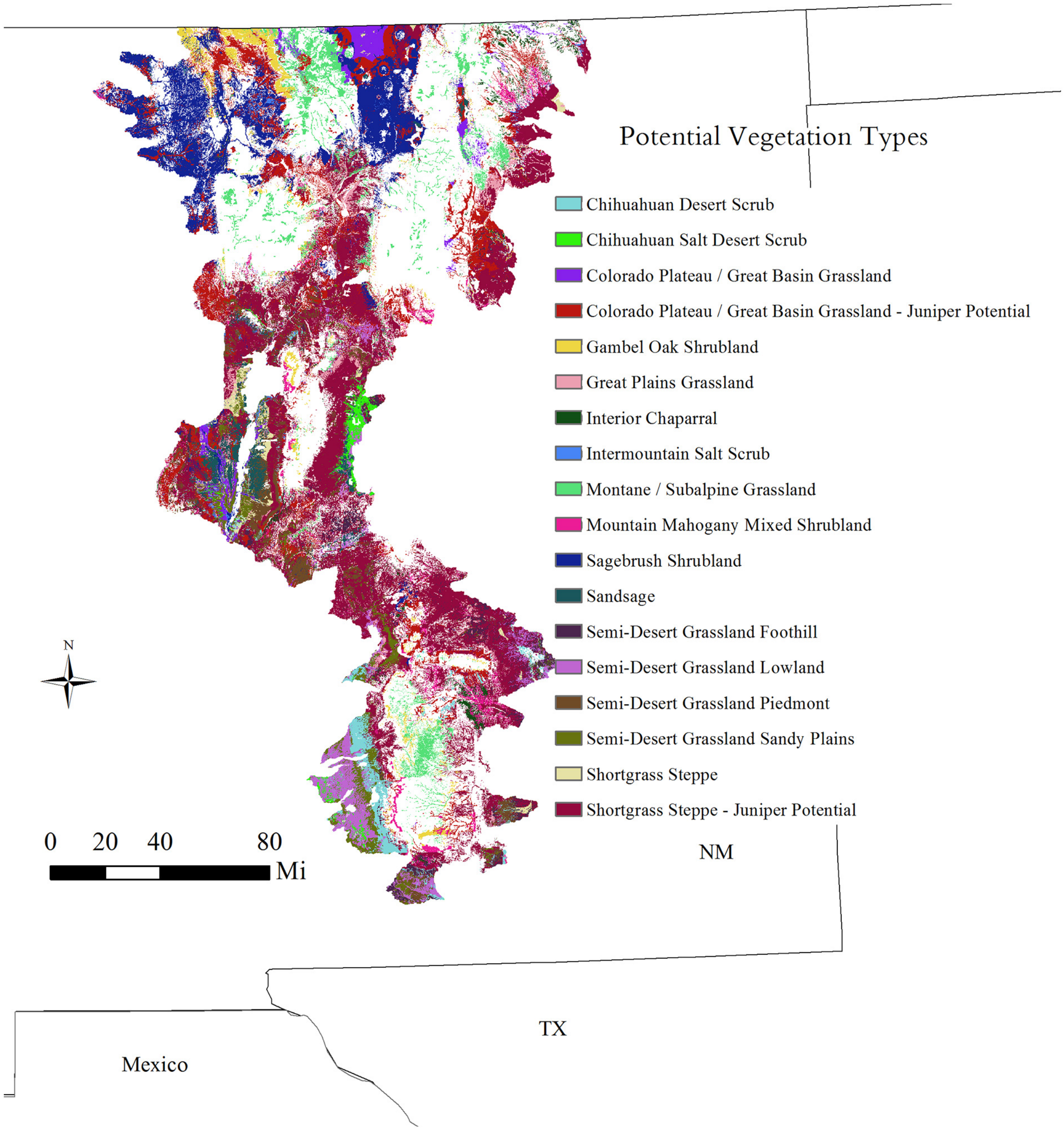

Figure 1. Study area and distribution of area (acres) by potential vegetation type for the study area.

adopted by the Intergovernmental Panel on Climate Change for the fifth Assessment Report (AR5).[12] The RCPs 4.5 and 8.5 used here represent potential radiative forcing values (W m^{-2}) in the year 2100 relative to preindustrial values (i.e., the RCP 4.5 scenario is one where an estimated additional 4.5 W m^{-2} of radiative forcing or insolation by 2100 will be present). Precipitation and temperature projections from each of these scenarios were used to infer annual net primary productivity (NPP) and drought transition probability by PVT (see below). Each climate scenario was replicated twice: with and without grazing. Scenarios were simulated for 99 years from 2000 to 2099 and 20 Monte Carlo realizations. Model projections were aggregated across climate models within each RCP with results showing the 95% confidence intervals across all 100 model realizations (5 unique GCMs by 20 iterations each) within each combination of RCP (4.5 and 8.5) and grazing scenario. The GCMs and RCPs were selected to match those being used for the national rangeland assessments being conducted for the Renewable Resources Planning Act (RPA) 2020 assessment (https://www.fs.fed.us/research/rpa/). For all scenarios and GCM combinations, separate model runs were conducted but the individual model runs were averaged for display and reporting purposes.

Table 1. The area of Potential Vegetation Types throughout the study area

Name (PVT)	Area (ac)	Proportion
Shortgrass Steppe – Juniper Potential	3,331,032	0.33
Colorado Plateau/Great Basin Grassland – Juniper Potential	1,329,967	0.13
Sagebrush Shrubland	1,311,155	0.13
Montane/Subalpine Grassland	578,464	0.06
Semi-Desert Grassland Piedmont	442,051	0.04
Semi-Desert Grassland Lowland	396,257	0.04
Semi-Desert Grassland Sandy Plains	359,751	0.04
Gambel Oak Shrubland	275,030	0.03
Great Plains Grassland	258,747	0.03
Mountain Mahogany Mixed Shrubland	255,922	0.03
Chihuahuan Desert Scrub	245,933	0.02
Colorado Plateau/Great Basin Grassland	238,325	0.02
Semi-Desert Grassland Foothill	247,603	0.02
Sandsage	239,590	0.02
Chihuahuan Salt Desert Scrub	111,456	0.01
Interior Chaparral	143,181	0.01
Intermountain Salt Scrub	65,336	0.01
Shortgrass Steppe	120,002	0.01

PVT indicates potential vegetation type.

Projections of Net Primary Production

Projections of NPP were produced in a two-step process. First the annual production in the present and near past (2000 to 2015) was estimated for each PVT. Each PVT was overlaid with the data contained in the Rangeland Production Monitoring Service (RPMS, https://www.fs.fed.us/rmrs/projects/development-rangeland-production-monitoring-service-could-improve-rangeland-management), which estimates rangeland production at each pixel in units of pounds per acre. This enabled the mean production and interannual variability to be computed in each PVT. In the second step, NPP anomalies were developed using projected precipitation following the process developed by Del Grosso et al., (2008) for nonforest ecosystems.[13] This approach is based on a simple regression model based on biome, temperature, and precipitation. For nonforested biomes such as the ones modeled here (grassland and savanna), the model relies solely on precipitation. The anomalies were produced as percentage values, which were subsequently converted to estimates of productivity in pounds per acre using the mean NPP data from the RPMS.

Projections of Drought

The documentation for the ILAP STSMs did not provide quantitative thresholds for the level of precipitation or resultant productivity that constitute drought-based transitions between vegetation classes. Thus to simulate the effects of drought on shifts in vegetation composition, we made the following assumptions: 1) because productivity in the semiarid systems being simulated is mainly driven by precipitation, we assumed a relationship between NPP and the probability of drought transitions; 2) we assumed that when annual NPP was above 400 pounds per acre, drought transitions would not occur; 3) we assumed that when annual NPP was below 300 pounds per acre, drought transitions would always occur in state classes that contained drought transition pathways; 4) between these two NPP thresholds we interpolated linearly to estimate the probability of drought transitions as a value between 0 and 1. Below 300 pounds per acre the probability of drought was 1, whereas at or above 400 the probability was 0. The threshold of 400 was chosen because it is just below the minimum observed NPP value across the study area over the historic time period (see Fig. S1), whereas the lower threshold of 300 was chosen because it is on the lower range of NPP values over the projection period. NPP varies between vegetation types and therefore the probability of drought also varies accordingly. Note that these thresholds do not define when "drought" has occurred but when the drought is severe enough that it results in a transition in vegetation state for some simulation cells.

Forage Use and Grazing Targets

The baseline levels of herbivory were estimated to be a function of current annual net primary production (from the

Picture 1. Shortgrass Steppe Juniper Potential. Photo courtesy of Iric Burden, USDA, NRCS.

RPMS) for each PVT (see current and historic production values in Fig. S1). Further, available forage estimates were constrained by a nominal utilization threshold of 35% and then multiplying the area of each PVT across the landscape for an estimate of average total forage available for use. These estimates of forage were divided by the amount of forage required to support a cow calf pair for 1 month (780 pounds; an Animal Unit Month [AUM]). Thus, the estimated capacity (AUMs per acre) was calculated each year as follows:

$$\text{Estimated capacity}(\text{AUM/acre}) = \text{NPP}(\text{lbs/acre}) * 0.35/780(\text{lbs/AUM})$$

Using these assumptions to provide baseline conditions for comparisons with future projections means that years in the future exhibiting production values near those of present day would require the entire landscape to be grazed evenly at a target of 35% of NPP. In contrast, years with higher production would require less than the entire landscape to be grazed, and years with lower than average production would not achieve utilization targets.

This analysis is not meant to produce a grazing capacity, but rather a relative indicator identifying the likelihood of achieving the assumed amount of herbivory relative to present day production dynamics. Note also that some state classes in the ILAP STSMs do not have grazing transitions, which means that grazing cannot be simulated across the entire landscape. Accordingly, if the composition of the landscape shifts to include more area in these state classes it becomes more difficult to achieve utilization targets because in the simulation, there is less "grazeable area". For example, the Colorado Plateau/Great Basin Grassland – Juniper Potential PVT only has grazing transitions defined for 2 of 8 potential state classes which include the Perennial Grass/Mid Shrub

Picture 2. Colorado Plateau Juniper Potential. Photo courtesy of Jack Triepke, USDA, USFS.

and the Perennial Grass state classes. As a result, if the simulated state composition shifts away from these state classes in that PVT, there is less area available for grazing, generally reflecting a limitation of the ILAP models.

Results and Discussion

Forage Use and Grazing Targets

Figure 2 summarizes the projected amount of forage consumed. The target consumption in scenarios with grazing

Picture 3. Sagebrush Shrubland. Photo courtesy of USFWS.

Table 2. Short description of climate scenarios used for state-and-transition simulation models				
Global Circulation Model	**RCPs**	**Grazing simulated?**	**Temperature response relative to baseline (C) $RCP_{4.5}/RCP_{8.5}$**	**Precipitation response relative to baseline (%)**
HadGEM2_ES	4.5 and 8.5	Yes	2.9/3.2	2.4/4.1
MRI_CGCM3	4.5 and 8.5	Yes	1.0/1.4	4/8.1
CNRM_CM5	4.5 and 8.5	Yes	2.0/2.3	9.8/8.1
bcc_csm1_1_m	4.5	Yes	1.6	−0.1
IPSL_CM5A_MR	8.5	Yes	3.0	−3.7
NorESM1_M	4.5 and 8.5	Yes	2.2/2.7	3.2/4.1

Note: The baseline period was 1971–2000 and the future period was 2031–2060.
RCP indicates representative concentration pathway.

for each year was 35% of historic average annual production. There are three types of results when looking across all PVTs. Some PVTs show a rapid decline in forage consumption rates (i.e., Colorado Plateau/Great Basin Grassland – Juniper Potential), whereas others show a more gradual decline (i.e., Sagebrush Shrubland). In many years during the projection period, utilization targets are achieved, but there are also many years that fall far short (e.g., Shortgrass Steppe). Forage use is slightly lower on average for RCP 8.5, probably because there are more extremely low production years for this RCP. The results are strongly influenced by the number of state classes with grazing transitions defined. The Shortgrass Steppe PVT shows a relatively constant amount of forage consumption over time, reflecting the general resistance of these sites to herbivory. Projections for the Colorado Plateau/Great Basin Grassland – Juniper Potential PVT show a rapid decline in forage consumption as the amount of area with defined grazing transitions rapidly declines.

The failure to achieve utilization targets are driven by two possible factors: 1) the disappearance of grazeable state classes (e.g., Colorado Plateau Great Basin Grassland – Juniper Potential and Sagebrush Shrubland) or 2) reductions in overall productivity as projected by the GCMs used for this study. For example, for the shortgrass-steppe PVT, after 2050 in the RCP 8.5 scenario, the amount of forage consumed is consistently less than 200 pounds per acre (Fig. 2). It is likely that the disappearance of grazeable state classes is an artifact of the decision by the original developers of the ILAP models to not include grazing transitions for all states where grazing is possible. Possibly because the intent of the ILAP models was not to evaluate the sustainability of grazing use rates, these pathways were omitted. Future work to make these models operational as a tool to evaluate grazing scenarios requires that careful consideration be given to identifying the model state classes where grazing is possible.

Vegetation Composition

For vegetation composition results, we focus on the three PVTs that are most prominent on the landscape (Fig. 1): Shortgrass Steppe – Juniper Potential, Colorado Plateau/Great Basin Grassland – Juniper Potential, and Sagebrush Shrubland. Although fire was simulated throughout the projection period (see Supplementary material for methods), there was almost no observed effect on vegetation state-classes. This is because throughout the historical period from 1984 to 2014, which was used to calibrate fire size and frequency, there is very little fire in these semiarid systems. To illustrate, 2006 was the year in which the greatest amount of fire occurred in the study area but, in total, only 0.0046 percent of the area exhibited any fire.

Figure 3 shows changes in the distribution of vegetation states for the Shortgrass Steppe – Juniper Potential PVT. For scenarios with grazing, there are minimal differences between RCPs and little variability between model iterations (recall that there are 20 iterations per climate model and RCP combination). For example, see how the lines for RCP 4.5 and 8.5 with grazing are nearly inseparable, especially for the Annual or Sparse Grass and Ruderal Grass state classes. This suggests, according to the pathways present in the ILAP models and the model assumptions used for each scenario, that the projected effect of grazing supersedes any effects of climate.

Most striking in the scenarios with grazing is the almost immediate disappearance of the Perennial Grass cover, which is consistently replaced first by Ruderal Grass and then by the Annual and or Sparse Grass state class. This almost immediate transition requires an examination of the assumed grazing effects on the Perennial Grass state classes. It is important to remember that the grazing targets used in this analysis were constant and did not vary with time, which is a constraint that managers are not necessarily limited to, especially if drier conditions persist.

In contrast to the grazing scenarios, scenarios without grazing show some differences between RCPs. For example, vegetation tends to be more variable on an interannual basis for RCP 8.5 than for RCP 4.5 scenarios, especially toward the latter half of the projection time period. The “sawtooth” pattern in the RCP 8.5 (with no grazing; Fig. 3) is generally caused by drought events of greater intensity in the RCP 8.5. When the irregular sawtooth pattern is shown, it means that

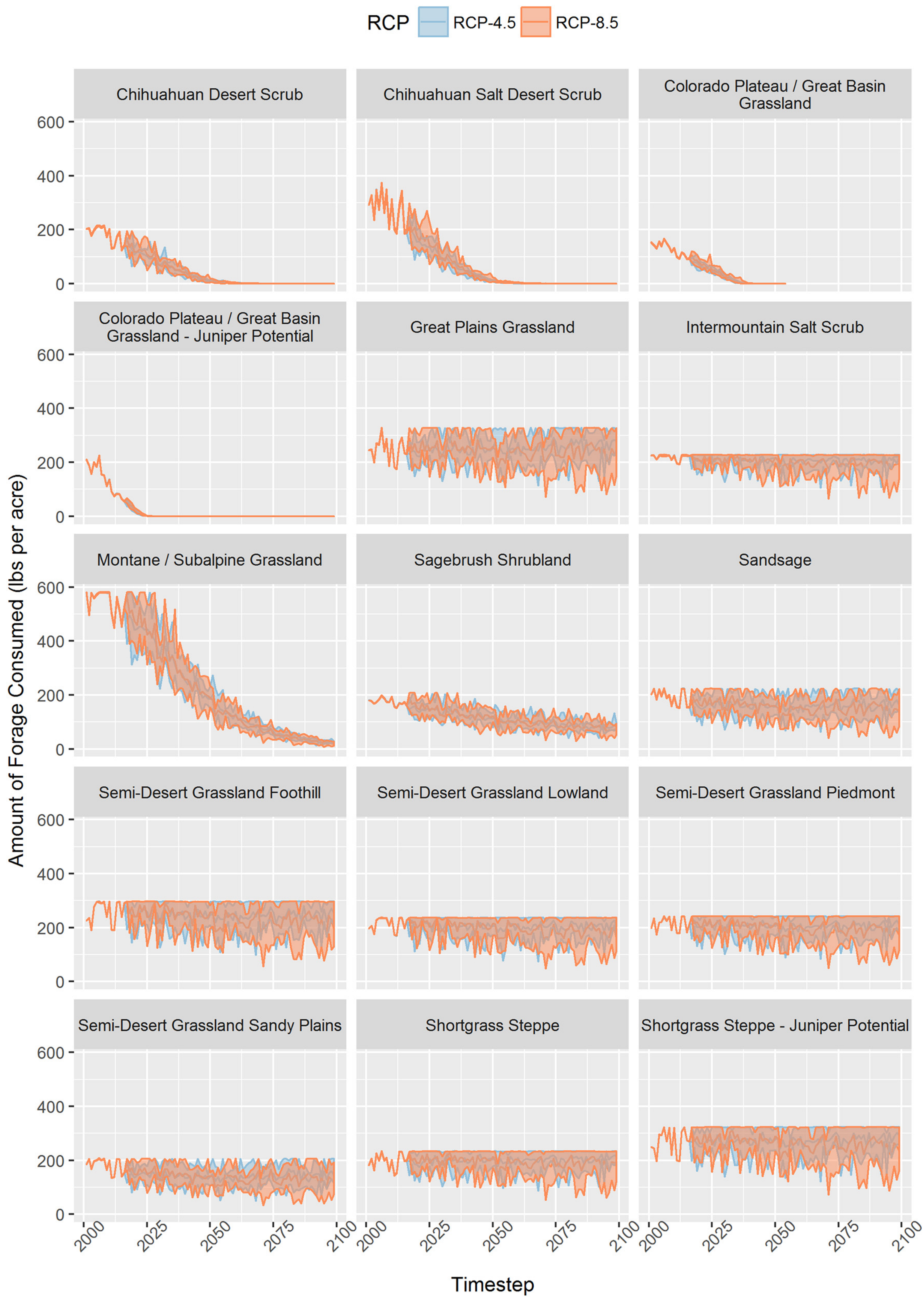

Figure 2. Forage consumption by potential vegetation type and RCP (representative concentration pathway). Model runs targeted a utilization rate of 0.35 of the average annual historic productivity. The shaded area represents the 95% Monte Carlo confidence intervals.

drought transition pathways are being invoked. The broader Monte Carlo confidence bounds also reflect greater uncertainty with increasingly long projection periods.

Figure 4 for the Colorado Plateau/Great Basin Grassland – Juniper Potential PVT shows the distribution of vegetation composition over time and, as with the Shortgrass Steppe –

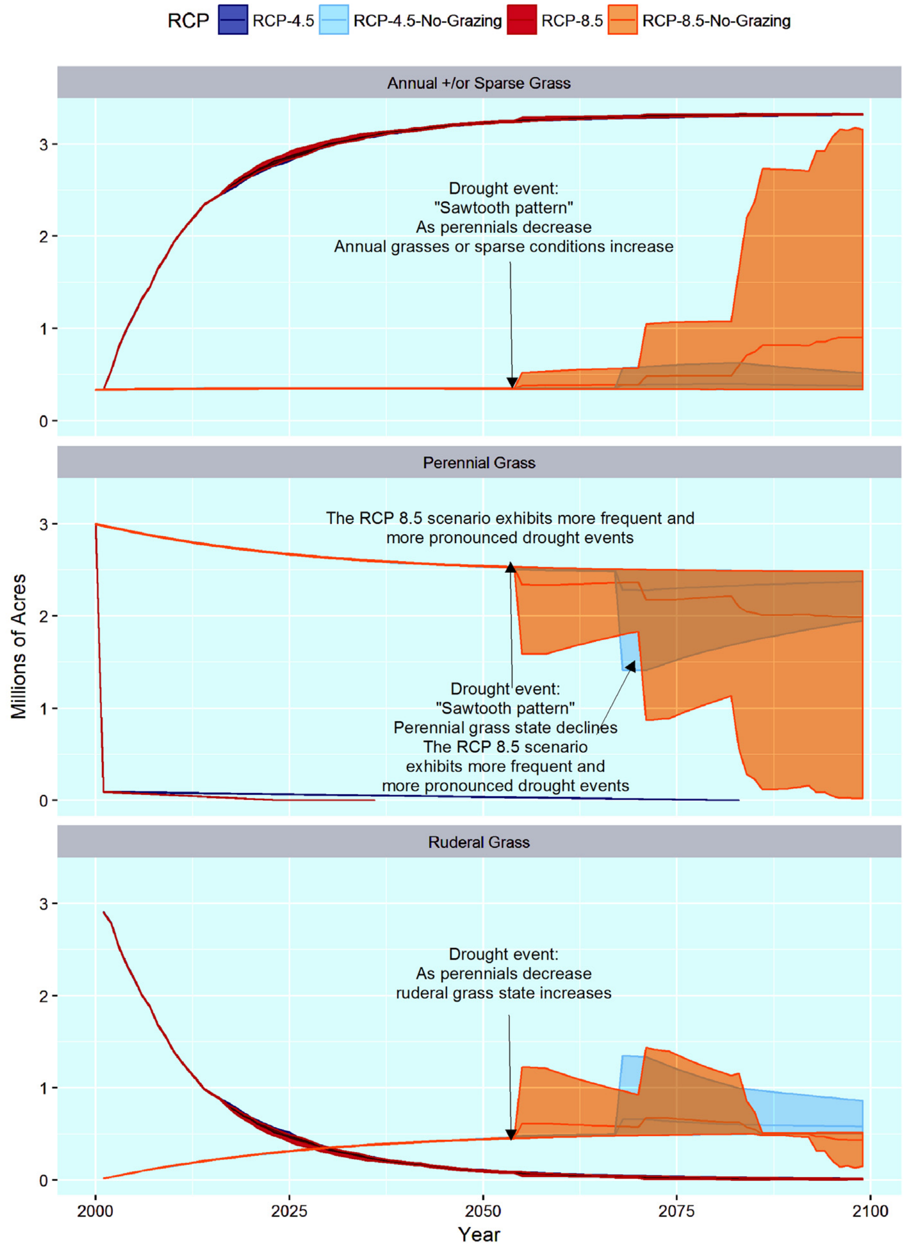

Figure 3. Landscape composition for the Shortgrass Steppe Juniper Potential PVT (Potential Vegetation Type) over time for two RCP (representative concentration pathway) scenarios with and without grazing. The shaded area represents the 95% Monte Carlo confidence intervals.

Juniper Potential, there are no real differences between RCP projections for scenarios with grazing. Unlike the Shortgrass Steppe, there are also no differences in RCP projections for scenarios without grazing.

All scenarios, whether grazing is permitted or not, show a rapid decline in perennial grass cover, with the decline being more rapid for scenarios with grazing. Scenarios with grazing show an eventual shift to state classes dominated by juniper with exotics, whereas scenarios without grazing shift in composition from perennial grass dominated communities to state classes with juniper and perennial grass. An important aspect of Figure 4 is that as the perennial grass cover disappears, it is replaced by less productive (and often less palatable) cover types such as juniper with exotics. However, in the scenarios with grazing, a consistent demand for forage is simulated thereby creating a feedback. Whereas less palatable and nutritious vegetation dominates the landscape, as increasingly greater grazing intensity is simulated on the remaining state classes that support herbivory which, in turn, speeds the transition to even less forage on the landscape. These types of simulated interactions and feedbacks are a central feature and benefit of STSMs.

Figure 5 for the Sagebrush Shrubland PVT shows the distribution of vegetation composition over time; for this

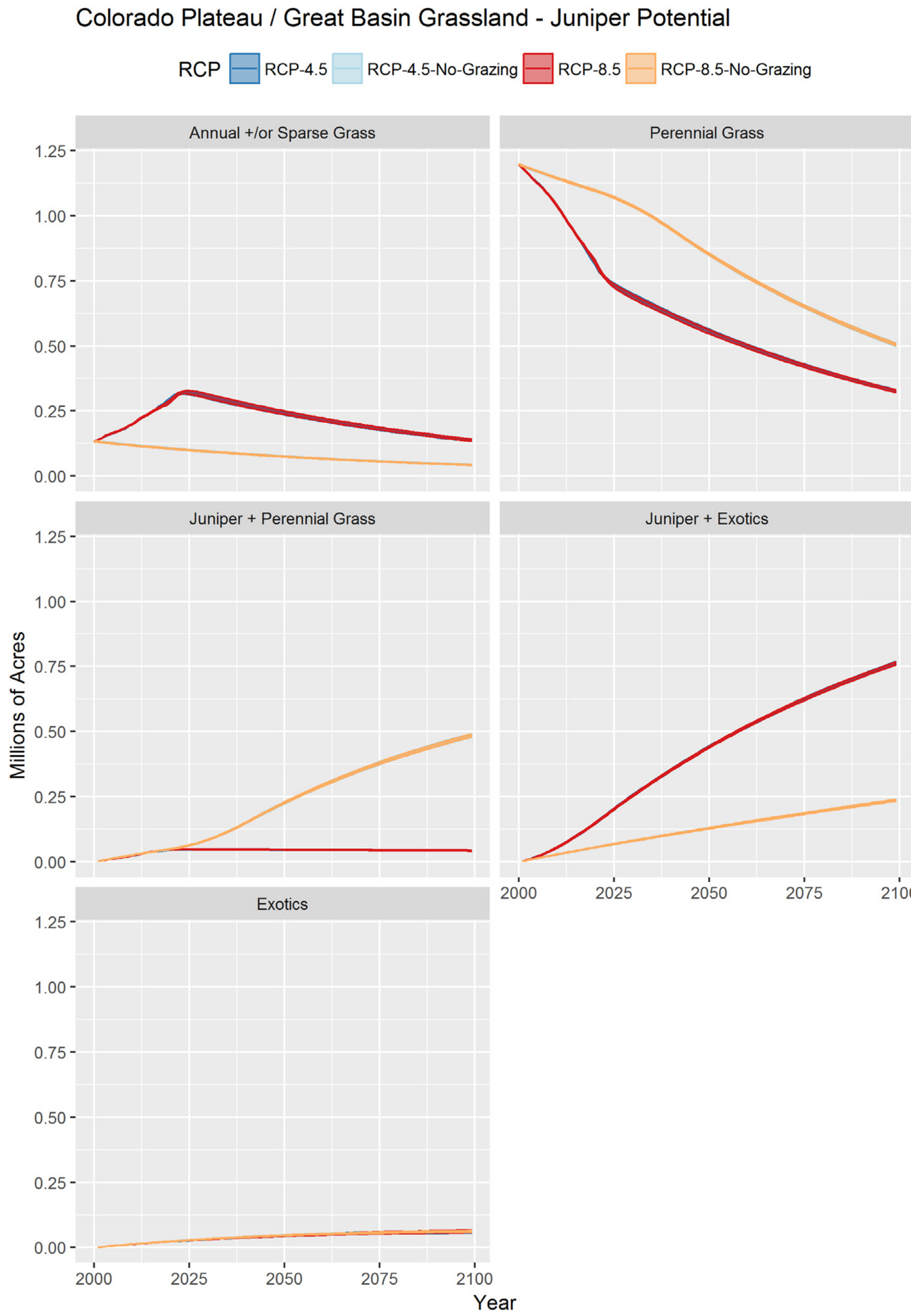

Figure 4. Landscape composition for the Colorado Plateau/Great Basin Grassland with Juniper Potential PVT (potential vegetation type) over time for two RCP (representative concentration pathway) scenarios with and without grazing. The shaded area represents the 95% Monte Carlo confidence intervals.

PVT, there are differences for all grazing scenarios between RCP 4.5 and 8.5. RCP 8.5 tends to have projections with more variable cover distributions between iterations and through time. On average, RCP 8.5 tends to have more area in vegetation communities dominated by perennial grass and less area in vegetation communities dominated by juniper. A dynamic that is unique to this PVT (compared with the others examined here) is that the juniper with perennial grass state class is being replaced with just perennial grass. This suggests that the drought transitions and pathways present in the ILAP models indicate juniper mortality from drought is occurring periodically. This does not mean that all juniper mortality is universal because the juniper with exotics class does increase with time in all scenarios.

Some of the model projections of vegetation composition indicate that there are gaps in the ILAP models that must be addressed before they can be applied to decision-making with respect to grazing. Some state distribution changes observed in our projections seem problematic. For example, in scenarios with grazing, there is an almost instantaneous disappearance of perennial grass communities in the Colorado Plateau/Great Basin Grassland – Juniper Potential PVT. These types of large

Figure 5. Landscape composition for the Sagebrush Shrubland PVT (potential vegetation type) over time for two RCP (representative concentration pathway) scenarios with and without grazing. The shaded area represents the 95% Monte Carlo confidence intervals.

changes are usually the result of model parameters, especially transition pathways and the probabilities associated with these pathways. Assumptions are necessary for these types of modelling exercises, but with respect to transition probabilities, it is important to understand that there are several ways to create more realistic pathways and probabilities. For example, data can be used to quantify changes that take place under experimental conditions. Likewise, as was done here, expert knowledge can be used along with trial and error and retrospective analyses where estimates are made using known environmental conditions (e.g., past management and weather). If these challenges with the models can be overcome, then this is a viable approach for conducting a landscape level risk analysis on the sustainability of grazing and its consequences on landscape vegetation dynamics under alternative climate scenarios. The important take-home message for these issues, however, is that the process demonstrated here can help foster the type of dialogue required to identify potential errors in the assumptions used. In short, the tool demonstrated here is a promising system for exploring the consequences of differing management viewpoints under varying expectations of short- or long-term climate scenarios.

Rangeland managers are continually expected to do more with less while producers operate on small margins. These complicated issues are exacerbated by the spectre of changing climates and will require us all to think outside the box. Part of thinking outside the box is exploring new or novel technologies that can aid development of strategies aimed at ensuring that goods and services will be available for future generations. Here we used STSMs to project vegetation response to management and climate. The work presented here is a first step toward assisting in resolving the complexities of management. These situations produce interactions that are impractical and almost impossible to quantify using traditional tools and techniques. Importantly, the techniques employed here build upon all the knowledge and expertise present in many conceptual STMs.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rala.2018.10.010.

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