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Diverse Management Strategies Produce Similar Ecological Outcomes on Ranches in Western Great Plains: Social-Ecological Assessment☆,☆☆

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ABSTRACT

Experiments investigating grazing systems have often excluded ranch-scale decision making, which has limited our understanding of the processes and consequences of adaptive management. We conducted interviews and vegetation monitoring on 17 ranches in eastern Colorado and eastern Wyoming to investigate rancher decision-making processes and the associated ecological consequences. Management variables investigated were grazing strategy, grazing intensity, planning style, and operation type. Ecological attributes included the relative abundance of plant functional groups and categories of ground cover. We examined the environmental and management correlates of plant species and functional group composition using nonmetric multidimensional scaling and linear mixed models. After accounting for environmental variation across the study region, species composition did not differ between grazing management strategy and planning style. Operation type was significantly correlated with plant community composition. Integrated cow-calf plus yearling operations had greater annual and less key perennial cool-season grass species cover relative to cow-calf—only operations. Integrated cow-calf plus yearling ranches were able to more rapidly restock following drought compared with cow-calf operations. Differences in types of livestock operations contributed to variability in plant species composition across the landscape that may support diverse native faunal species in these rangeland ecosystems. Three broad themes emerged from the interviews: 1) long-term goals, 2) flexibility, and 3) adaptive learning. Stocking-rate decisions appear to be slow, path-dependent choices that are shaped by broader social, economic, and political dynamics. Ranchers described having greater flexibility in altering grazing strategies than ranch-level, long-term, annual stocking rates. These results reflect the complexity of the social-ecological systems ranchers navigate in their adaptive decision-making processes. Ranch decision-making process diversity within these environments precludes development of a single "best" strategy to manage livestock grazing.

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Introduction

Sustainability of family ranches depends on adaptive decision making within the ranch enterprise and the broader social and ecological systems in which it is embedded (Marshall and Smajgl, 2013; Wilmer and Fernández-Giménez, 2015; Roche et al., 2015b). However, rangeland science has developed limited capacity to document, interpret, and support adaptive management because research has insufficiently considered linkages between grazing management strategies and resulting ecological outcomes at spatial and temporal scales relevant to ranch decision makers (Lubell et al., 2013; Roche et al., 2015a). Limited integration of the social and ecological components of rangeland systems in research has contributed to a large gap between scientific and management knowledge. This is clearly evident in the ongoing debate regarding the perceived benefits of different grazing management strategies (Briske et al., 2008; Teague et al., 2008; Briske et al., 2011; Provenza et al., 2013; Teague et al., 2013; Briske et al., 2014; Roche et al., 2015a).

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☆☆ Integrated Social-Ecological Approches to Silvopastoralism (Huntsinger and Plieninger, editors).

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Social scientists recognize that grazing management is not driven entirely by vegetation and livestock production variables commonly examined in grazing experiments (Roche et al., 2015a). Instead, rancher decision-making takes into account complex, context-specific social-ecological interactions, often addressing both financial and ecological objectives, and relies upon multiple forms of rangeland management knowledge at broad spatial and temporal scales (Brunson and Burritt, 2009; Budd and Thorpe, 2009; Ellis, 2013; Hruska et al., 2017; Roche et al., 2015a; Roche et al., 2015b; Wilmer and Fernández-Giménez, 2015). Stocking rate decisions are particularly complex, and are expected to pose continued economic challenges for ranchers adapting to increasingly variable climatic conditions across the Great Plains of North America (Hamilton et al., 2016; Mu et al., 2013; Joyce et al., 2013; Polley et al., 2013; Ritten et al., 2010; Torell, 2010). Although considerable research exists on the financial and ecological implications of stocking rate and grazing intensity (Bement, 1969; Derner et al., 2008; Dunn et al., 2010; Hart et al., 1988; Holechek, 1988; Mu et al., 2013; Reeves et al., 2015) our understanding of on-ranch grazing decision-making is less well developed (Rowe et al., 2001; Grissom and Steffens, 2013; Kachergis et al., 2014). Additionally, rangeland scientists recognize that the ecological outcomes of livestock grazing often manifest over time scales of one to several decades, though traditional grazing management experiments rarely occur at these time scales (Milchunas et al., 1994; Porensky et al., 2016; Sanderson et al., 2016; Augustine et al., 2017).

Lubell et al. (2013) proposed a theoretical framework to link social and ecological relationships in rangeland systems. It theorizes that adaptive feedbacks between social and ecological processes across multiple spatial and temporal scales are influenced by a rancher decision maker's goals, capacity, values, beliefs, and access to information through social networks while he or she learns and adapts to both social and ecological dynamics (Fig. 1). However, the hypothesized relationships in this framework, particularly between grazing management strategies and the resultant ecological outcomes, remain to be tested on working ranches (Roche et al., 2015a).

Here, we evaluate and refine the Lubell et al. (2013) conceptual framework for ranch-scale social-ecological interactions. Specifically, we 1) test the links between rancher decision making and ecological outcomes (Holling and Gunderson, 2002; Marshall and Smajgl, 2013); 2) elucidate ranch adaptive decision-making processes through qualitative interviews (Sayre, 2004); and 3) discuss the implications of the identified decision-making processes to the larger grazing systems debate (see earlier). We evaluated the conceptual framework using a combination of rancher interviews and vegetation monitoring (plant species and functional group composition) for 17 ranches in eastern Colorado and eastern Wyoming.

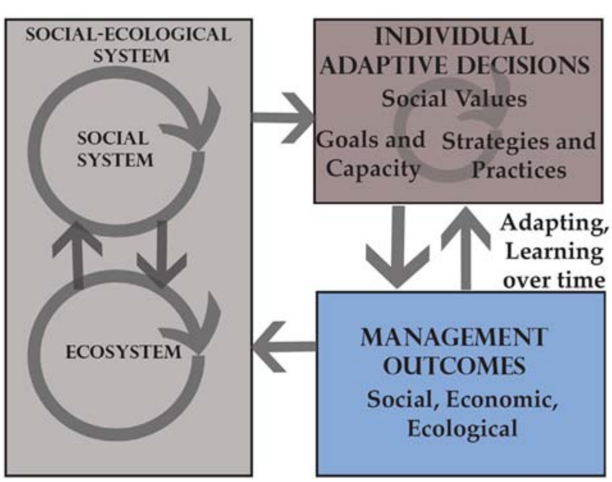

Figure 1. Conceptual framework. Lubell et al.'s (2013) theoretical framework for ranch decision-making hypothesizes links between individual ranch management decisions, management outcomes and broader social-ecological dynamics.

Methods

Study Area

We conducted our study in the western North American Great Plains, where plant species and functional group composition are important indicators of rangeland biodiversity, hydrologic function, and productivity and are influenced by grazing management, environmental variability, and evolutionary history of grazing (Milchunas et al., 1989). Furthermore, vegetation composition influences livestock weight gains (Derner et al., 2008) and economic returns for ranchers (Manley et al., 1997; Hart and Ashby, 1998; Dunn et al., 2010). Biophysical drivers of plant species composition include spring precipitation (Lauenroth and Sala, 1992), catena position, soil texture, and temperature (Epstein et al., 1997). Within this biophysical setting, stocking rate experiments have clearly shown that season-long heavy-grazing intensity induces slow, continuous, and directional changes in vegetation composition via replacement of cool-season perennial grasses with less productive warm-season perennial grass species (Milchunas et al., 1994; Hart and Ashby, 1998; Derner and Hart, 2007; Porensky et al., 2016) and moderate increases in bare ground (Augustine et al., 2012). Also, heavy grazing reduces the ability of cool-season perennial grasses to respond to precipitation variability (Irisarri et al., 2016).

The study area is characterized by a north-south gradient in mean annual temperature (7 − 11°C) and a west-east gradient in mean annual precipitation (339 − 460 mm) (Fig. 2). Native plant communities within this region are dominated by warm-season shortgrasses (primarily *Bouteloua gracilis* and *Bouteloua dactyloides*), cool-season midgrasses *(Pascopyrum smithii, Hesperostipa comata),* and cool-season sedges (*Carex* spp.), with increasing dominance of cool-season gramminoids in the northern, cooler portion of the study area and dominance of warm-season shortgrasses in the southern, warmer portion (Lauenroth et al., 1999; Lauenroth and Burke, 2008).

Our sampling approach identified individual ranches in our study area and then categorized ranches on the basis of an analysis of their self-reported, ranch-scale management practices of all land they managed in some manner (deeded, leased, and government permits). Ranches with similar management practices were grouped together, and ecological monitoring data were statistically compared across groups of ranches. We studied 17 beef cattle ranches distributed across a latitudinal gradient ranging from approximately 39.882 to 42.821°N and from − 102.150 to − 105.217°W, with seven ranches in Wyoming and 10 in Colorado. All were family-owned cow-calf or cow-calf plus yearling ranches. Potential ranch participants were identified through network sampling from the ranching community known to the research team and their agricultural networks (Noy, 2008). This case selection technique follows replicate, not sampling, logic and seeks to identify groups of ranchers with similar qualities, not to sample across a distribution of a specific population. Network sampling is often used in case study and qualitative social research to identify multiple cases that will provide insight into a specific phenomenon and to aid in theory development, and it is not meant to provide a random sample of cases for statistical generalization across a population (Yin, 2013).

Social and Management Data Collection

We used repeated, semistructured ethnographic interviews to identify themes in rancher decision-making processes at time scales that encompass ranchers' lifetimes and multigenerational planning horizons. These data also allowed us to identify specific management practices in place for 10 yr or more that we could use to compare ecological conditions across groups of ranches that shared the same practices. Figure 3 provides a summary of the methods, including data collection and

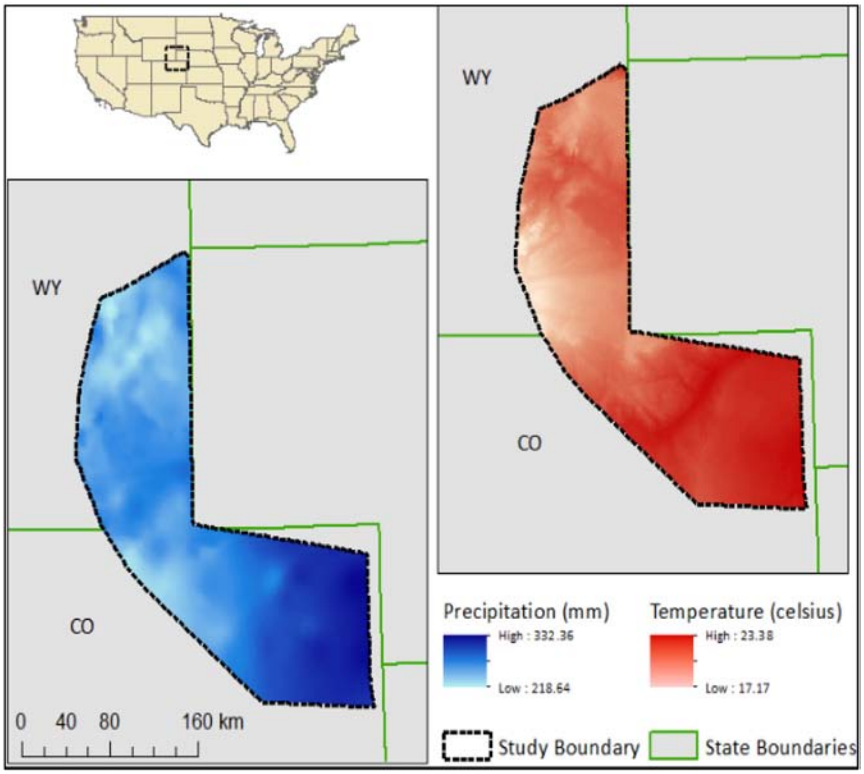

Figure 2. Study area. We selected 17 beef cattle operations distributed across a latitudinal gradient in the North American Great Plains characterized by a north-south gradient in mean annual temperature and a west-east gradient in mean annual precipitation. Ranch locations are confidential.

analysis. We conducted and audio recorded initial interviews on nine ranches in 2012 and added eight ranches in 2014. We conducted follow-up interviews each summer from 2014 to 2016. Initial semistructured interviews focused on questions about ranch operation structure, goals, criteria for success, grazing management strategies, and annual decision-making triggers. These interviews included discussion of a ranch map, when available. In subsequent interviews, ranchers were asked to describe major changes in their grazing management and

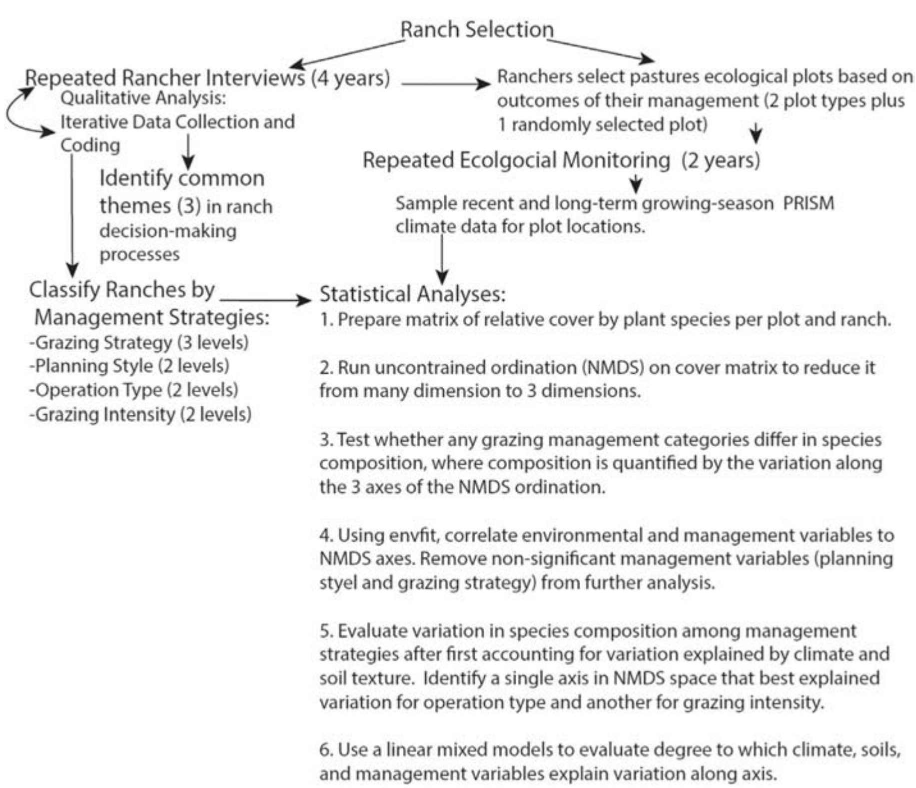

Figure 3. Research process. Steps for data collection and analysis for both social (repeated interviews) and ecological (species composition) data.

other decisions on the ranch, as well as to describe their perspectives of social, economic, and ecological outcomes of those decisions relative to fluxes in market, climatic, and social change. These questions were intended to illicit a better understanding of ranchers' adaptive decision making using an ethnographic approach.

Interviews were conducted on the ranches, with the exception of two phone interviews. A total of 30 ranchers were interviewed (17 men, 13 women), representing the 17 ranches. All members of ranching families were invited to participate. Interviews involved one to five people, ages from mid-20s to mid-80s, two generations in four cases (including couples and their children in three cases and a father/daughter ranching team), couples in five cases, and individual primary decision makers in seven cases (five men and two women). All interviewees were white. Ranchers who participated in the study for 3 yr were offered a cash honorarium in 2016. This study was approved by Colorado State University IRB protocol 12-3381H, and participation in the study was confidential.

Ecological Data Collection

We developed a protocol to monitor three locations (plots) on each ranch. Ranchers agreed to give us limited access to their pastures and monitoring data, and our team attempted to limit inconvenience to ranchers, who sometimes accompanied us in monitoring. Ranchers helped to identify two pastures on their ranches that they wanted monitored: one that represented best outcomes of their management and another that had the most improvement possibility for forage production from the rancher's perspective. A plot was established within a representative area of both pastures identified by individual ranchers. Researchers identified a third, randomly selected pasture and randomly placed a plot within it. Subsequent analysis found no statistical differences in species composition between rancher-selected and randomly selected plots within a ranch. In 2014 and 2015, we measured basal cover of plant species, litter, moss/lichen, biological soil crust, and abiotic attributes (soil, rock, and dung) using the line-point intercept method (Godínez-Alvarez et al., 2009) with measurements (see Supplemental Material A, available online at https://doi.org/10.1016/j.rama.2017.08.001) taken every 0.91 m along two, 50-m transects on each plot following a modified NRCS Natural Resources Inventory protocol (US Department of Agriculture, 2011).

Soil cores were collected at 0- to 10-cm depth and 10- to 20-cm depth (10.19-cm diameter) at each plot, and clay content was determined with the hydrometer method (Bouyoucos, 1962). Using latitude and longitude coordinates from the center of each plot, we obtained long-term precipitation and mean temperature data for the growing season months (April — August) from the Parameter-elevation Relationships on Independent Slopes Model (PRISM, 2004; Daly et al., 2008) 30-yr normal product (1981 — 2010) at 800-m resolution. Spring precipitation (April — May) proportion was calculated from the total growing season (April — August) precipitation. We derived elevation, slope, and aspect from 1 arc-sec resolution ASTER global digital elevation models (NASA JPL, 2009).

Data Analysis

Rancher Interviews

We used an iterative qualitative coding process to identify core themes in rancher decision making and categorize individual ranches by management strategies (Gibson and Brown, 2009). This included reading and rereading interviews, as well as identifying and classifying ranchers in terms of their actions, beliefs, and interpretations of ranching. To do this, we sorted qualitative data and interpretive notes into a priori and emergent codes and sorted codes into major themes using a computer spreadsheet. These codes included descriptions of grazing management decisions, major changes on the ranch, sources of and barriers to flexibility, and management goals. The themes were concepts identified in each of the 17 cases that brought meaningful context to the relationships among manager goals, social values, and learning and adaptation over time as hypothesized by Lubell et al. (2013).

To ensure the validity of the qualitative data, we had prolonged engagement with the data and conducted member checking by gathering feedback on our initial findings with rancher participants at subsequent interviews (Lincoln and Guba, 1986). We also conducted peer debriefing with three researchers who were not involved in the study. Peer debriefing is similar to an initial peer review, where qualitative researchers present memos and initial findings to other researchers to cross-check their interpretations. We also collaborated with a rancher (coauthor Kevin Miller) who interpreted how the three themes applied to his ranch decision making. We maintained a data audit trail, including clear documentation of raw data and descriptions of decisions about data reduction and synthesis, and triangulation of the data with researcher field notes and documents, including rancher-conducted research and monitoring results, provided by ranchers (Lincoln and Guba, 1986; Creswell, 2012). The qualitative research tradition recognizes that the subjective positions of different researchers may lead to different interpretations of the same data and calls for researchers to reflect on how their positionality may have influenced their results—a practice known as *reflexivity* (Lincoln and Guba, 1986; Creswell, 2012). In this study, the lead author reflected on her own position through audio journaling and writing (Wilmer, 2016).

Ranch Management Variables

Using the interview data, we classified each ranch according to grazing strategy, planning style, grazing intensity, and operational type on the basis of ranchers' reported management during the past decade. Three grazing strategies (extensive, moderate, and intensive) were assigned on the basis of 1) few pastures, long grazing duration—weeks to months (extensive); 2) many pastures, moderate grazing duration—many weeks (moderate); and 3) many pastures, shorter grazing duration—days to weeks (intensive) (Roche et al., 2015a). Planning style (two levels) was assigned to each ranch according to the extent to which managers engaged in explicit or tacit grazing management planning. Explicit planning involved development and reevaluation of goals, overt grazing planning, record keeping, and adjustment of grazing management practices between and within years based on documented events or new information. Tacit management planning included unwritten or unspoken traditions, lack of documentation of grazing planning or records, and adjustments to management without documented rationale. Ranches were assigned to either high or low grazing intensity on the basis of being above or below, respectively, the study-wide mean of rancher-reported maximum land base (10 ha) managed to support an animal unit equivalent year-round (excluding irrigated cropland). Operation type for each ranch was classified as either a cow-calf — only operation or a cow-calf — plus yearling operation based on activities over the past decade. Operations were categorized as cow-calf only if they kept their own replacement heifers but did not keep other yearlings for outside sale. We did not sample yearling-only ranches.

Ecological Variables

We calculated species composition by averaging 2014 and 2015 basal cover data for each plot and relativizing to total plant basal cover. We removed rare species occurring on < 5% of plots, checked for outliers based on a nearest-neighbor criterion using the R library 'dave' (McCune et al., 2002; Wildi, 2010), and transformed the relative species cover data to down-weight dominant species. We performed all ecological data transformations and analyses in R (R Core Team, 2016). We derived rangeland functional group data from untransformed basal cover (including rare species) relativized to total cover by plants and nonbiological cover types. On the basis of growth habit, photosynthetic pathway, and palatability, we categorized all recorded plants into the following functional groups: shrubs/subshrubs, palatable cool-season perennial grasses, unpalatable cool-season perennial

Box 1
Rancher interpretation of themes. Kevin Miller, a Colorado rancher, describes how the three themes of rancher decision making relate to his cow/calf plus yearling (seed stock) operation. Miller, 44, is an explicit grazing planner who runs the operation with his wife, in-laws, and two hired hands. In our study, this ranch is classified as a high-grazing intensity ranch, under an intensive grazing strategy.

Rancher's Perspective on Grazing Management

by Kevin Miller, Croissant Red Angus, Briggsdale, CO

Theme 1: Long-term goals

Our family operation began in 1996 with a holistic view of resource management, and with the goal of leaving the resources in better condition for the next generation. We achieve this goal by analyzing the needs of the components of the ranch and leveraging interactions to achieve greater operational success. Our approach is not just about each pasture improving; it's about the entire system improving. At the end of the day, the grass root source is basically our factory. There's always improvements that we can make within our factory to make things more efficient and better.

Theme 2: Flexibility

Progress toward our goals has been slow and is greatly influenced by precipitation patterns. These patterns are reflected in our grazing records, which show changes in stocking rates from year to year. Our philosophy is never to manage to the extreme, but to manage to just below the mid-line on our stocking rate. In those really dry years, it's hard to find enough grazing for the cows we have, but in the really wet years extra grass may go to seed and we can use the forage later. For drought management, we have increased our forage base by adding acreage to the ranch. We also destock in drought by reducing our animal numbers and weaning early, and we use grassbanked pastures. Our grazing system allows flexibility to manage grazing duration and rest in a pasture, and to graze pastures at different times across years. Originally the ranch had 12 pastures. We subdivided these into 52 smaller pastures and have spent years developing reliable water system using pressure tanks from wells and solar pumps. This strategy minimizes the labor required to check and move cows in the many breeding groups that make up our complex breeding system.

Theme 3: Adaptive learning

Ranching traditions offer a good starting point to learn from. We pull the good points from tradition and leave the bad points behind. In a business sense, we move at a much faster pace than previous generations had to. As a resource manager, I am responsible for making sure that all facets of the business work together. That becomes challenging as you look at rates of change in various parts of the business, each component moves differently. Our initial phase of developing infrastructure (fence and water systems) and our grazing rotation is plateauing. We are now working on smaller land purchases, wildlife fencing, and developing new relationships with our customers. Our goals have not changed but will continually be modified as we learn more from the information we gather. Strides toward success have been challenging. Every decision we make involves going through the cost-benefit analysis. We analyze data before we step off to do something new, in hopes of making better decisions in the future.

grasses, shortgrass *(Bouteloua)* species, other warm-season perennial grasses, annual grasses, annual forbs, and perennial forbs. Bare ground, dead plants, litter, moss/lichen, biological soil crust, rocks, and dung were also classified as groups.

Linking Ranch Decision Making and Ecological Data

To interpret the influence of environmental drivers and management categories on rangeland species composition, we first performed a Non-metric Multi-Dimensional Scaling (NMDS) ordination using the Bray-Curtis dissimilarity (Kruskal, 1964) of the log-transformed cover data. We chose NMDS, a nonparametric, unconstrained ordination technique, because of the method's ability to handle nonlinear species responses to environmental gradients (McCune et al., 2002; Oksanen et al., 2016). We ran NMDS for one through six dimensions and selected the optimal number by examining the stress versus dimensionality for each solution (McCune et al., 2002).

To test whether management strategies differed in species composition, we used the function 'envfit' (permutations = 999). This function allowed us to correlate management categories and environmental variables with NMDS axes and displayed scaled significant ($P < 0.05$) environmental variables as vectors on the ordination plots (see Supplemental Material B, available online at https://doi.org/10.1016/j.rama.2017.08.001). Management variables that were not significantly correlated with the NMDS ordination were excluded from further analysis. To understand the relationship between NMDS axes and strategies, while accounting for environmental variables, we first rotated the NMDS ordination with the first dimension parallel to significant management strategies so that the first axis explained the most variation in the data correlating to each strategy (we conducted one rotation for grazing intensity and another for operation type). We then extracted the site scores for the respective rotated axes.

We fit linear mixed models (LMMs) using the lme4 package in R (Bates et al., 2015) to predict the site scores on each rotated NMDS axis. LMMs allowed us to evaluate site scores along the rotated axis as an indicator of species composition in reduced dimensional space by accounting for the environmental variation on each ranch. We used Akaike Information Criteria (AIC) to select the final models. For the scores extracted from the NMDS axis rotated parallel with grazing intensity, the final model fixed effects included soil clay content, grazing intensity, total growing season precipitation, and mean growing season temperature, and ranch was the random effect (Table 2). For the scores extracted from the NMDS axis rotated parallel with operation type, the final model fixed effects were aspect, soil clay content, spring precipitation, operation type, and slope, and ranch was a random effect (Table 3). Finally, to understand the differences between management strategies in rangeland functional group composition (based on vegetation functional groups and nonbiological cover), we used similarity percentage analysis via the "simper" function in the vegan R library (Oksanen et al., 2016) to calculate the overall contribution of rangeland functional groups to the Bray-Curtis dissimilarity of plots in different management groups.

Results

Common Themes in Grazing Management Decision Making

Below we describe the three major themes we developed from interviews with 30 ranchers on 17 case study ranches: 1) long-term goals, 2) flexibility, and 3) adaptive learning. We describe each theme and provide illustrative examples from the qualitative data below. Co-author rancher Kevin Miller further describes his interpretation and application of these three themes in Box 1.

Theme 1: Long-Term Goals

Ranchers chose grazing management strategies that they believed supported an overall goal to maintain their ranching operations, both economically and ecologically, over their lifetime and often for multiple generations. For example, a rancher from Wyoming described his ranching goal to steward the land and business for years to come: *"There's just something to stewardship that says you save the ranch for future generations"*. He described a conceptual link between his ranch's operational structure, selection of strategies and practices, and goal for long-term stewardship. This rancher indicated that his grazing management strategies supported the slow, continuous improvement of ranch profitability over his lifetime as measured by the shrinking proportion of calf sales that went to loan payments. This theme was expressed in interviews across ranches in this study, with two exceptions. One ranch couple indicated that they were willing to seek out other professions if their quality of life or ranch profitability objectives were not met and that they did not expect their children to take over the ranch. Another rancher focused on shorter time horizons than others because he doubted that ranching would be a viable livelihood "in 50 years" (or in his grandchildren's lifetime) due to continued declines in ranch profitability and increased public pressure to remove public lands grazing programs.

Theme 2: Flexibility

Ranchers indicated that they chose strategies they perceived would create flexibility and limit risk exposure in highly localized ecological and ranch infrastructure contexts and under highly variable climatic and market conditions. Across the 17 study ranches, ranchers described diverse perspectives on the best ways to promote management flexibility. Ranchers employing moderate and intensive grazing strategies generally emphasized decisions that increased their control of grazing processes over space and time. In contrast, those using extensive grazing strategies generally emphasized the importance of adapting to uncertain weather, market, and ecological conditions. Ranchers in Wyoming generally emphasized building flexibility through their use of heterogeneous landscapes at different times of year, as well as hay production and storage, while Colorado ranchers emphasized greater dependence on croplands, feedlot enterprises, and diverse income streams.

Flexibility in grazing season stocking-rate decision making was especially important in dry years with reduced forage availability. Ranchers maintained this flexibility in many ways. For example, a Wyoming couple (Rancher A = husband, Rancher B = wife) described their decision-making and learning processes during 3 dry yr in 2002, 2004, and 2006:

> Rancher A: "We had to [sell our yearlings] a lot in the early 2000's, when we just kept hitting those droughts every other year. You just get rid of the steers and that opens up pasture [for our cow-calf pairs]. If we didn't have those steers, we probably would have been selling a lot of pairs."
>
> Rancher B: "Then buying them back when they cost a lot. Instead, we are able to come back without buying any outside cattle."
>
> Rancher A: "We got hit the first time in 2002. That was our first time with drought and I was kind of fishing in the dark there. We kept half the steers and half the heifers. In 2004 we got into it again. That year was different because there was no water on our summer pastures. And then 2006 was a repeat of the 2002 thing. By that time we'd been through it enough, we knew to just get rid of the all the steers and go ahead and put the cows on feed, in a feedlot in Nebraska. We've got a template of what to do in drought, and depending on the markets and what things are doing we adjust accordingly."

This interview excerpt illustrates how ranchers combined flexible stocking rates with other sources of forage to adjust to variable rainfall and market conditions. Cow-calf operators were generally less willing and able to flex their annual stocking rates as quickly; rather, they described grazing "grass-banked" residual forage from rested or lightly used pastures and using social and familial networks to find access to additional forage. One cow-calf operator in Colorado said she built flexibility into her operation by partnering with her brother's farm:

> "We have flexibility. We have our own hay—we grow our own. My brother has a few pastures, a few little pastures that we don't utilize every year, and we can bring them in service. It makes it nice to be able to move around a little bit. Plus, when drought comes and the price of hay goes up, we have hay to sell."

Theme 3: Adaptive Learning

Ranchers frequently indicated that they had "improved" their ranch management over time. In this context this refers to efforts to increase organization, efficiency, and profitability through betterments made to the overall ranch business infrastructure, livestock health and performance, and other specific management objectives through adaptive learning. Their learning experiences were linked to their personalities, personal experiences, and the trajectory of the ranch family and business over generational time frames (Hurst et al., 2017; Wilmer and Fernández-Giménez, 2016). For example, a ranching family on a cow-calf plus yearling operation in Wyoming learned over the primary operator's lifetime to organize their high grazing intensity and moderate grazing strategy around multiple factors. These included consideration of elevation and precipitation gradients, plant species phenology, livestock nutrition and reproductive requirements, family labor constraints, and management of invasive annual grasses. Here, the primary operator learned to take advantage of complex topography and variation in plant community types to maintain flexibility to address within-growing season weather variability. He said that drought and transition planning were two opportunities to make positive changes to management on their ranch.

Interviews generally suggest that most frequently, rancher learning manifested through incremental changes to ranch operations. In contrast, four ranchers described making rapid, dramatic changes to their operational structure and grazing management strategies during their

Table 1
Management variables. Cross-tabulation of rancher membership in categories of management variables.

Operation type	Grazing strategy	Planning type	Grazing Intensity		Total
			High	Low	
Cow-calf			4	3	7
	Extensive		3		3
		Tacit	2		2
		Explicit	1		1
	Moderate		1	3	4
		Tacit	1	3	4
Cow-calf + yearling			7	3	10
	Extensive		2	2	4
		Tacit	2	1	3
		Explicit		1	1
	Moderate		1	1	2
		Tacit		1	1
		Explicit	1		1
	Intensive		4		4
		Tacit	4		4
Total			11	6	17

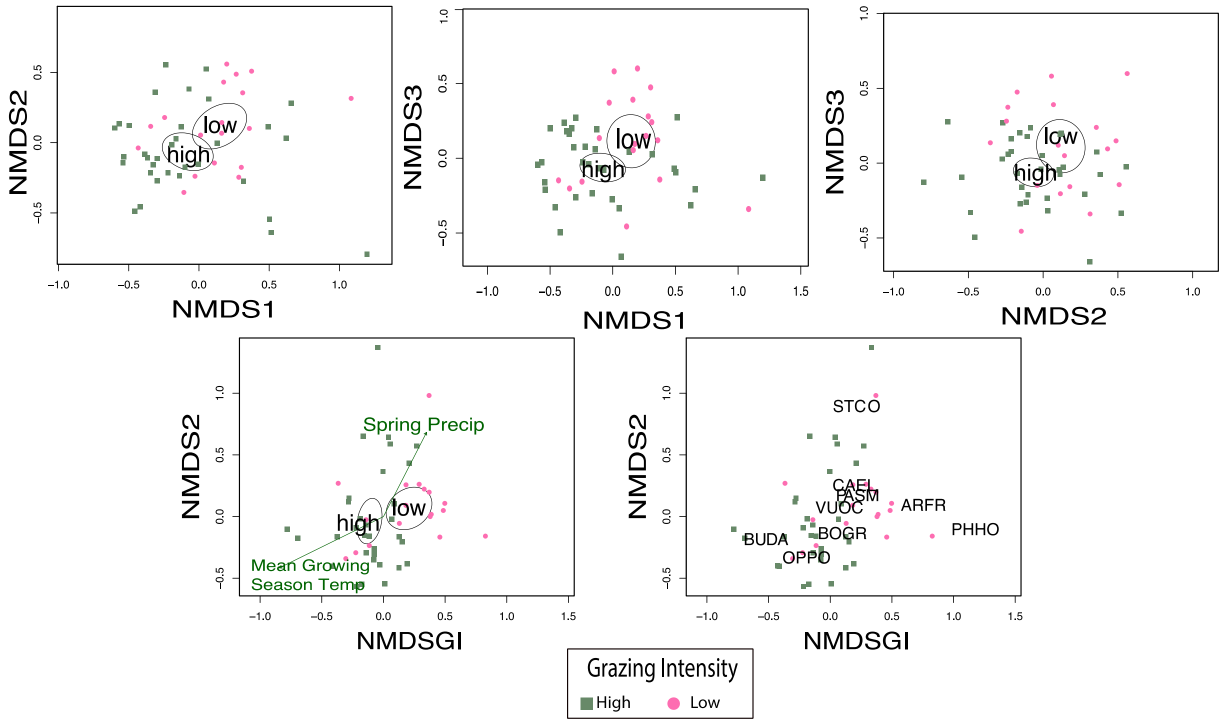

Figure 4. Plant species composition by grazing intensity. Top row: NMDS ordination plot shows the comparison of species composition by grazing intensity group. The centroid of each grazing intensity group is enclosed in a 95% confidence ellipse. Bottom row: We rotated the ordination so that axes NMDS GI was parallel to grazing intensity and added vectors for environmental variables significantly correlated ($p < 0.05$) with the NMDS ordination (bottom left frame). Plots found closer to species (4-letter codes) have more relative abundance of that species in reduced-dimensional space. TM = mean growing season temperature (30-year normal), PPTSpring = proportion of growing season precipitation that falls in the spring (30-year normal). Species shown account for 73% of the Bray-Curtis dissimilarity between intensity groups (bottom right frame).

respective ranching careers. Kevin Miller (Box 1) explains that the rate of ranch decision making varies across generations and within one rancher's tenure. Ranches that did make dramatic changes cited educational and social networks, drought, low market prices, and (in one case) loss of forage to fire as inspirations for dramatic change and "faster" learning.

Management Strategies

Repeated semistructured interviews documented on-the-ground management strategies ranchers used to maintain enterprise viability and stewardship of rangeland ecosystems (see Table 1). Our study identified seven ranches using extensive grazing, six moderate grazing strategies, and four intensive grazing strategies. Two ranches employing extensive duration, one ranch with moderate duration, and all intensive rotational strategies used explicit planning styles. Planning style was not clearly linked with rancher age or sex. We categorized 11 ranches as "high" grazing intensity and six as "low" grazing intensity. Seven were primarily cow-calf operations (including replacement heifers), and 10 included yearling herds in their cow-calf enterprises.

Ecological Results

The NMDS ordination (stress = 0.138, k = 3, nonmetric $R^2 = 0.98$) did not show distinct clustering of species composition for ranch grazing strategy or planning style management groups (Fig. 4 and Supplemental Material B). These categories were not significantly correlated with the NMDS ordination.

Categorizing ranches by grazing intensity did cluster ranches into distinct groups that differed in plant species composition (Fig. 5). The NMDS axis rotated to parallel with grazing intensity (Axis NMDS GI on Fig. 5 and Table 1) separated the "low" grazing intensity sites with a greater abundance of perennial cool-season grasses and sedges (*P. smithii, Poa secunda, Carex* spp., *Hesperostipa comata, Elymus elemoides*), perennial forbs *(Astragalus/Oxytropis, Sphaeralcea coccinea),* subshrubs *(Chrysopsis villosa, Artemisia frigida),* and annual forbs *(Plantago patagonica, Leucocrinum montanum)* from the "high" grazing intensity sites with a greater abundance of annual cool-season grasses *(Bromus tectorum, Vulpia octoflora),* an unpalatable perennial warm-season grass *(Aristida longiseta),* cacti *(Opuntia polyacantha),* and palatable warm-season grasses *(B. dactyloides, Sporobolus cryptandrus).*

Categorizing ranches by operation type (cow-calf or cow-calf plus yearling) groups also clustered ranches that differed in plant species composition (Fig. 6). The NMDS axis rotated parallel to operation type (NMDS OT on Fig. 6 and Table 2) separates cow-calf operations with a greater abundance of specific cool-season perennial grasses *(P. smithii, P. secunda)* and perennial forbs (*Astragalus/Oxytropis*) from cow-calf plus yearling operations with a greater abundance of subshrubs *(A. frigida, Gutierrezia sarothrae),* annual cool-season grasses *(B. tectorum, V. octoflora),* and annual forbs *(P. patagonica, L. montanum).*

Pair-wise comparison of (relative untransformed) rangeland functional group contributions to Bray-Curtis dissimilarity between management groups (Fig. 7) indicates that litter (LIT), *Bouteloua* (BOBU), bare ground (BARE), annual cool-season graminoids (ACSG), dead plants, and perennial cool-season graminoids, including sedge species (PCSG), together accounted for ~82%—83% of the Bray-Curtis dissimilarity between operation types and between grazing intensity groups.

Discussion

Repeated rancher interviews provide insight into how ranchers make meaning of the complex world in which they must make decisions (Sayre, 2004; Atkinson and Delamont, 2006; Charmaz, 2006). Ranchers' emphasis on long-term goals (Theme 1) shows the value of maintaining ranching livelihoods and cultures for multiple generations to the ranchers we interviewed. It suggests they have developed planning horizons that align with the slow pace of ecological change and their limited ability to adjust long-term stocking rates. We interpret the linked social and ecological aspects of rancher goals as a reflection

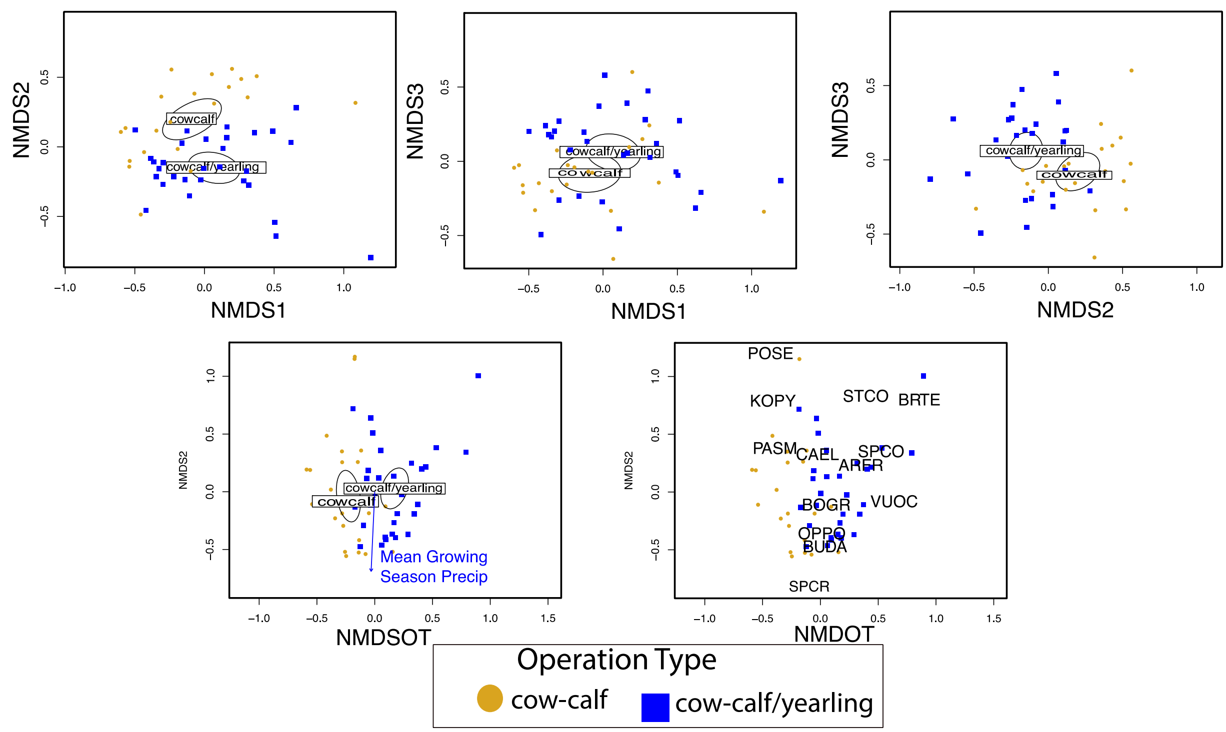

Figure 5. Plant species composition by operation type. Top row: NMDS ordination plot shows the comparison of species composition by operation type. The centroid of each group is enclosed in a 95 % confidence ellipse. Bottom row: We rotated the ordination so that axes NMDS OT was parallel to operation type and added vectors for environmental variables significantly correlated (($p < 0.05$) with the NMDS ordination (bottom left frame). Plots found closer to species (4-letter codes) have more relative abundance of that species in reduced-dimensional space. TM = Mean growing season temperature (30-year normal). Species shown account for 74% of the Bray-Curtis dissimilarity between intensity groups (bottom right frame).

of ranchers' perception that "doing good" in terms of plant species composition has a mutually reinforcing relationship with livestock performance and financial "doing well" (Derner et al., 2009; Dunn et al., 2010; Huntsinger et al., 2012; Macchi et al., 2013; Huntsinger and Oviedo, 2014). Ranchers' objectives for long-term ranch viability may also be a response by ranchers and their communities to broader cultural, economic, and land-use change at local and regional scales (Brunson and Huntsinger, 2008).

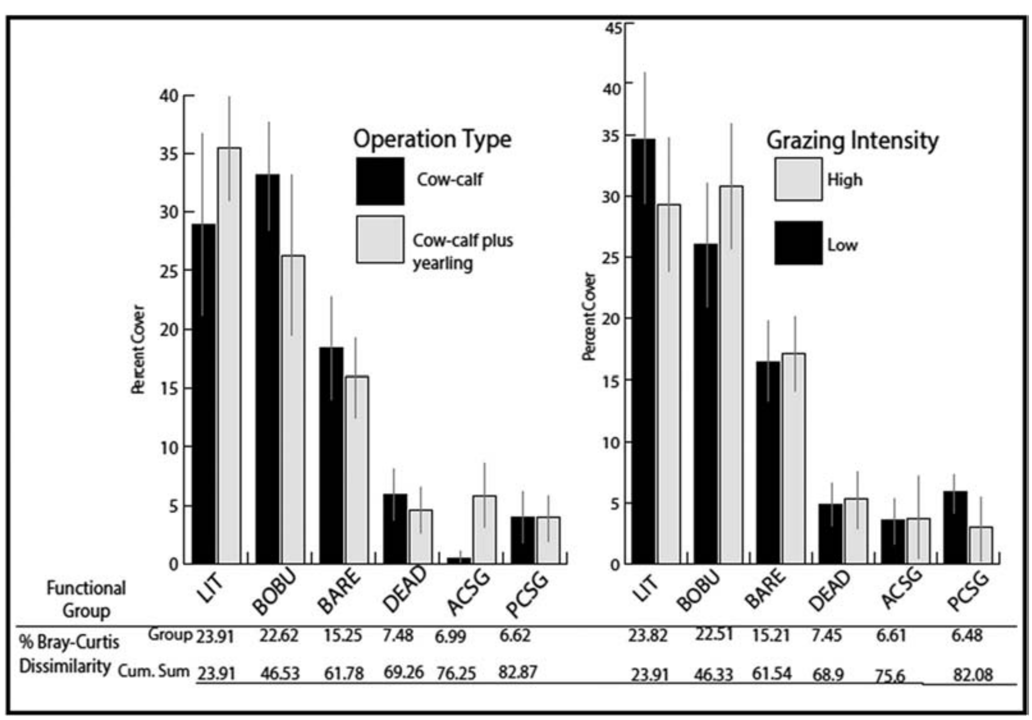

Figure 6. Plant functional group cover. Comparison of mean cover of functional groups by management strategy arranged by descending contribution to Bray-Curtis dissimilarity between strategies. For operation type and grazing intensity, litter (LIT), *Bouteloua* (BOBU), bare ground (BARE), annual cool-season graminoids, (ACSG), dead plants, and perennial cool-season graminoids (PCSG) together accounted for 82% of the Bray-Curtis dissimilarity between ranches with only cow-calf herds and those with cow-calf and yearling herds. Error bars are 95% confidence intervals for overall group abundance. NOTE: the PCSG group here includes a wide range of species (see Supplemental Material A).

Table 2
Summary of model selection based on Akaike Information Criteria (AIC) for plots grouped by grazing intensity (GI).

Model	Fixed effects	AIC	Δ AIC	Log likelihood
1	Clay + GI + PPT + MT	−7.5	0	10.74
2	Clay + GI + PPT + SP + MT	−6.2	1.29	11.09
3	Aspect + Clay + GI + PPT + MT	−5.9	1.58	10.95
4	Clay + GI + PPT + Slope + MT	−5.9	1.59	10.95
5	Clay + GI + PPT + SoilAg + MT	−5.5	1.98	10.75
Null	PPT + MT + Aspect + Slope + SP + Clay + SoilAg	2.2	9.7	8.91

SP indicates proportion of growing season precipitation that falls in the spring; PPT, total growing season precipitation; MT, mean growing season temperature; Clay, soil clay content (mean 0 − 20 cm); SoilAg, mean soil aggregate stability.

Flexibility (Theme 2) highlights rancher perceptions that maintaining the ability to modify decisions and management strategies was important to the success of their individual operations. Managers practicing moderate and intensive rotational grazing strategies emphasized the importance of infrastructure intensification for creating flexibility, an "intensification-for-flexibility" conceptual framing. We interpret the intensification-for-flexibility framing as a means to facilitate control, or limit variability, within complex ranching systems (Holling and Meffe, 1996), specifically through management actions perceived to change animal distribution, forage utilization, and species composition. Ranchers consistently emphasized flexibility as an important component to their decision making, but they were better able to build flexibility into their grazing strategies than into their stocking rate decisions. Markets are generally oversupplied with livestock during a drought but undersupplied when cow-calf producers buy back after a drought (Torell, 2010). Ranchers also acknowledged the irreplaceable value of their herd genetics and knowledge of local pastures.

Ranchers' emphasis on adaptive learning (Theme 3) is an important aspect of their capacity to adapt to climate and economic variability (Marshall and Smajgl, 2013). This theme also highlights the constraints path-dependent ranching operations face in adapting to climatic, economic, social, and ecological dynamics that are often beyond their control. Outreach and extension programs aimed at supporting adaptive decision making in semiarid rangelands will likely be more successful if they incorporate an understanding of rancher life courses and the long time scales (lifetimes and generations) on which managers grapple with social and ecological complexities (Hurst et al., 2017).

Differences in plant species composition between cow-calf and cow-calf plus yearling operations were associated with greater cover of annual cool season grasses and less cover of desirable, perennial cool-season grasses (e.g., *P. smithii*, *P. secunda*) on integrated cow-calf plus yearling operations. This likely resulted from 1) seasonally grazing pastures with yearlings at the same time each year, as moderate to heavy stocking rates reduce this perennial cool-season grasses (Hart, 1993; Manley et al., 1997; Derner and Hart, 2007; Porensky et al., 2016) and 2) more rapid and consistent restocking of yearlings compared with cows following drought (Kachergis et al., 2014), resulting in pastures receiving a cumulative greater grazing pressure. Cow-calf operators indicated that they had a limited ability to recover following destocking during drought and restocked slowly by retaining more heifers or purchasing additional females. Cow-calf ranchers typically reached their full stocking potential 3 − 4 yr following culling during drought conditions, while cow-calf plus yearling operators were able to fully restock in 1 − 2 yr. Because of the limited flexibility with stocking rates, cow-calf ranchers described creative means to cope with limited forage during dry times, including using social networks to access additional pastures, storing hay, and "banking" grass via planned resting or limited use of some pastures on the ranch (Kachergis et al., 2014).

Table 3
Summary of model selection based on Akaike Information Criteria (AIC) for plots grouped by operation type (OT).

Model	Fixed effects	AIC	Δ AIC	Log likelihood
1	Aspect + Clay + OT + SP + Slope	−22.5	0	19.27
2	Aspect + Clay + OT + Slope	−21.5	1.07	17.73
3	Aspect + Clay + OT + SP + Slope + MT	−21.4	1.15	19.67
4	Aspect + Clay + OT + SP	−21.2	1.29	17.62
5	Aspect + Clay + OT + SP + Slope + SoilAg	−20.9	1.59	19.47
Null	PPT + SP + MT + Aspect + Slope + Clay + SoilAg	−11.11	11.39	15.56

SP indicates proportion of growing season precipitation that falls in the spring; PPT, total growing season precipitation; MT, mean growing season temperature; Clay, soil clay content (mean 0 − 20 cm); SoilAg, mean soil aggregate stability.

An important aspect of this work is that we categorized ranch management variables on the basis of ranchers' self-reported practices over the past decade, though many had maintained similar stocking rates and operation types over longer periods. Therefore, there may be time lags in vegetation response to grazing management and/or legacy effects of past management that influence these results (Manley et al., 1997; Teague et al., 2013).

Although we documented significant plant species compositional differences between the relative high versus relative low grazing intensity ranches, including differences in abundance of cool-season perennial grasses, we do not suggest that either relative grazing intensity group represents a "better" or more sustainable grazing strategy. From an economic perspective, both grazing intensity groups included ranches that have been financially successful for multiple decades, but we do not have data to conclude whether the ecological conditions we measured have been maintained over time, or how more cool-season annual grasses abundance found under higher grazing intensities will impact ranch viability over the long term. From an ecological perspective, variation among ranches in grazing management can be a valuable source of ecosystem heterogeneity within landscapes. For example, plant communities with taller, structurally more complex canopies provided by cool-season perennial grasses provide habitat for different species of native vertebrates than do the short, sparse canopies in communities dominated by warm-season shortgrasses (Thompson et al., 2008; Derner et al., 2009; Augustine and Derner, 2015). To the extent that variation among ranches in grazing management strategies contributes to variability in plant communities, it can also help to sustain habitats for a diverse suite of native faunal species in these rangeland ecosystems. Conversely, outreach efforts that emphasize a single grazing management strategy as being the "best" or most optimal strategy for a particular region could suppress plant community diversity, habitat heterogeneity, and biodiversity (Fuhlendorf et al., 2012).

The implications of this investigation to the rotational grazing debate closely parallel those drawn from a much larger survey of California and Wyoming ranchers by Roche et al. (2015a, 2015b). The ranchers that we interviewed had broadly adopted rotational grazing strategies, but they varied widely in pasture number and periods of grazing and rest and none of them conformed to the description of short-duration grazing systems (with grazing periods in the order of 1 to a few days). We envision that rancher diversity in the major components of the adaptive decision-making framework (Lubell et al., 2013) would readily contribute to the development and implementation of the diverse grazing management strategies that we documented. Grazing management strategy did not modify vegetation composition independent of grazing intensity, which is consistent with the majority of experimental grazing research (Briske et al., 2008; O'Reagain and Scanlan, 2013). The insights derived from these in-depth rancher interviews both provide greater understanding of the grazing system debate and further indicate that the gap between management and scientific knowledge may not be as great as previously assumed (Roche et al., 2015a, 2015b).

Implications

Large variation in grazing management strategies among the 17 case study ranches is consistent with well-documented diversity within ranching communities (Kachergis et al., 2013a; Marshall and Smajgl, 2013; Roche et al., 2015a). We take this recognition of rancher diversity a step further by demonstrating that varied grazing management strategies may have only a minimal effect on ecological outcomes such as rangeland vegetation composition. Ranchers consistently emphasized flexibility as an important component to their decision making, but they were better able to build flexibility into their grazing strategies than into their stocking rate decisions. One important exception occurred between cow-calf and cow-calf enterprises that maintained yearling animals. Yearlings provide the ability to more rapidly restock following drought, resulting in pastures receiving a cumulative greater grazing pressure that modified community composition. An emergent benefit of varied grazing intensities among types of ranches is greater vegetation heterogeneity within the regional landscape.

Collectively, our results reflect the complexity of the social and ecological systems within which ranching enterprises function. Ranchers' intentions to achieve multiple long-term goals, manage with flexibility, and learn and adapt over time were primarily focused on grazing management strategy because these decisions take place at a scale where managers have the most capacity to act. However, stocking rate decisions are linked to socioeconomic scales that exist well beyond the family ranch, including sophisticated, globally integrated commodity markets, technological developments, agricultural policies and regulations, and broader geographic shifts in agricultural industries (Turner, 1993; Hruska et al., 2017). This suggests that the emerging adaptive decision-making framework (Lubell et al., 2013) should be expanded to explicitly integrate cross-scale interactions between ranch-scale decision making and broader social, economic, and political dynamics as we further develop conceptual models for rangeland social-ecological systems.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rama.2017.08.001.

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