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# Practical considerations for adaptive strategies by US grazing land managers with a changing climate

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**Abstract**

We outline practical considerations for grazing land adaptations with a changing climate, with an emphasis on the ranch operation scale and specific attention to directional climate changes and increased climate variability. These adaptive strategies fall into two themes: flexibility and learning under uncertainty. Ranches and livestock operations with greater land, social, or other capital resources may have more flexibility. Risk can be reduced for managers (ranchers, farmers, operators, and livestock managers) through participation in conservation or farm policy programs and/or market-based approaches. Bolstering adaptive capacity across landscapes and time can originate from social capital of operators and strategic collaborations among managers and scientists. As climate diverges from historical baselines and the realm of managers' experiential knowledge, new conceptual frameworks are needed to structure conversations, influence research relevancy and impact, and drive imaginative solutions among researchers, managers, and local communities for socio-ecological systems. We provide simplified frameworks to help guide conversation, future research, and new imaginative solutions for systems-scale knowledge needs and adaptation to address increasingly uncertain and complex change at multiple scales. Practical considerations for adaptive strategies by grazing land managers with a changing climate will be accelerated through (1) collaborative efforts among managers and explicitly with science–management partnerships becoming more mainstream, (2) co-produced research with managers and researchers at ranch scales, (3) development of communities of practice and associated learning opportunities, and (4) continued co-development and advancement of technologies and tools that result in high uptake adoption by ranch managers.

# 1 | INTRODUCTION

Managers of grazing lands, which include ranchers, farmers, operators, and livestock managers, in the United States have a wide assortment of tools in their toolbox for adapting to the biological and ecological impacts of climate change. Around the country, managers apply an assortment of strategies using ruminant livestock (e.g., cattle, sheep, and goats) to achieve desired production and conservation goals from US grazing land social-ecological systems (Wilmer et al., 2018a). Livestock can also enhance efficiency of crop production, including cover crops and annual forages, through consumption of plant residues and increased rates of nutrient cycling. US grazing lands encompass private- and public-owned rangeland, pastureland, grazed forestland, native and naturalized pastures, hayland, and grazed croplands. These grazing lands comprise of diverse soils, climates, elevations, plant communities, grazing animals, and operate under many regulatory frameworks and land tenure arrangements, management legacies, and forms of experiential knowledge. Therefore, there are a multitude of potential landscapes on which managers can employ adaptive strategies in the face of a changing climate. Practical considerations for adaptive strategies need to be front and center at the ranch (operation) scale to increase rates of adoption by managers. Benefits of increased adoption include enhanced resilience of grazing land ecosystems, the sustainable provision of desired ecosystem services, greater ranch profitability, and enhancement of rural and local economies, as well as reducing risk for the individual operation.

Research and practical experience related to climate adaptation tools has increased rapidly for grazing lands. The overall goal of this paper is to synthesize research related to tools available for US grazing land managers to adapt to both directional climate change and increased climate variability. We first review the current state of grazing land livestock production in the United States, and then present conceptual frameworks for adaptation to two aspects of climate change, directional change, and increasing variability. We conclude with practical considerations for adaptive strategies by grazing land managers with a changing climate related to collaborative efforts, co-produced research at ranch scales, development of communities of practice and associated learning opportunities, and continued development and advancement of technologies and tools for adoption by managers.

**Core Ideas**

- Directional climate changes and increased climate variability influence practical considerations for adaptation.
- Overall themes of grazing lands adaptive tools for managers are flexibility and learning under uncertainty.
- Climate and ecological dynamics are diverging from baselines and the realm of manager's experiential knowledge.
- Systems-scale knowledge needs and adaptation address increasingly uncertain and complex change at multiple scales.
- Collaborative or "co-produced" research develops new ways to improve applicability of real-world context.

# 2 | GRAZING LANDS LIVESTOCK PRODUCTION IN THE UNITED STATES

There are 236.3 million hectares (584 million acres) of privately owned grazing lands in the United States (USDA-NRCS National Resources Inventory, Figure 1). Most of the public-owned grazing lands are rangelands in the 11 western states and encompass 62.7 million hectares (155 million acres) managed for grazing by the Bureau of Land Management in the Interior Department, and 78.1 million hectares (193 million acres) of National Forests and Grasslands managed for grazing by the Forest Service in the Department of Agriculture. In addition, grazing leases are allowed on vast tracts of state-owned lands; for example, Montana has >2 million hectares (>5 million acres). Some 22.5 million hectares (55.7 million acres) are in trust for Native Americans (Native Land Information System, 2022, https://nativeland.info/blog/dashboard/usda-census-of-agriculture-for-american-indian-reservations/), and much of that acreage is considered grazing lands. Land ownerships and jurisdictions of management are particularly complex in the western United States. Loss of grazing lands to exurban development, conversion to crops, or other non-grazing uses not only removes forage resources but also reduces wildlife habitat and increases fragmentation, causing conservation and agroecological sustainability concerns (Augustine et al., 2021; Swette & Lambin, 2021).

Ruminant livestock uniquely convert the high cellulose biomass of plant materials produced on US grazing lands into a renewable human dietary source of energy and protein. Ruminants host specialized microbes in their digestive system which serve as the energy brokers between cellulose in plant biomass and the energy and protein available for human consumption. On US grazing lands, primary ruminant livestock include cattle, sheep, and goats. These species may spend all or some of their lives on grazing lands. For example, it is common for cattle and sheep to be born and reared in a grazing land context but finished in confined feeding settings.

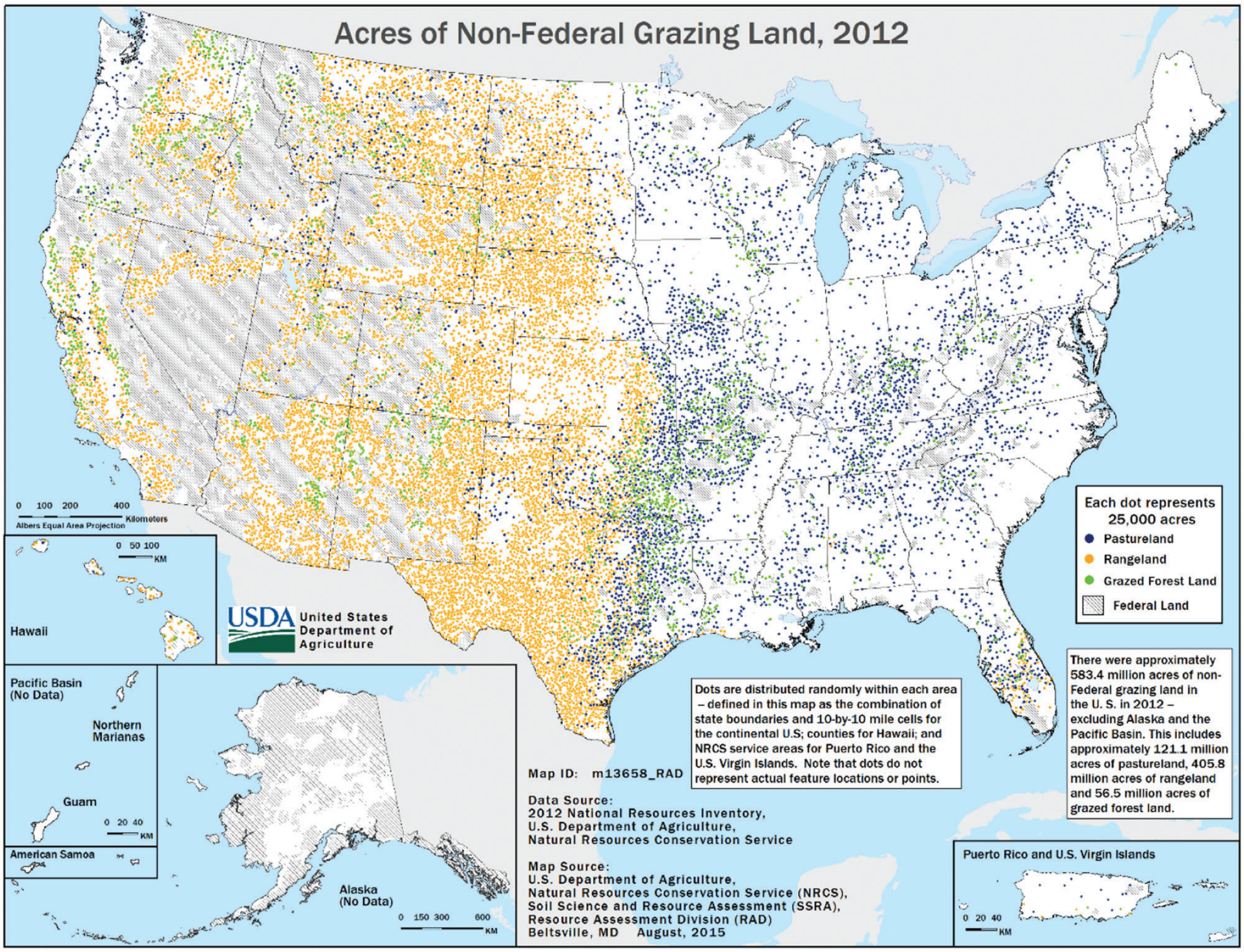


**FIGURE 1** Extensive non-federal grazing lands (including pastureland—blue dots, rangeland—orange dots, and grazed forest land—green dots) in the United States totaling 236.3 million hectares (584 million acres in 2012).

The predominant ruminant on US grazing lands is beef cattle. The January 1, 2022 USDA National Agricultural Statistics Service reported 91.9 million cattle and calves (beef and dairy) in the United States. Of the 39.5 million cows and heifers that had calved, 76% of these were beef, with 73% of the calves born in 2021 during the first half of the calendar year (January–July). The top 10 US states in numbers of beef cows that calved represent 59% of the total US herd, with 9 of the top 10 states in the Great Plains, where private grazing lands are well integrated into the beef production life cycle, with the exception being Kentucky (Table 1). In 2017, 1.3 million head of beef cattle and calves were reported on Native lands with about 0.32 million of those owned by native farmers (NASS, Native Land Information System, 2022; https://nativeland.info/blog/dashboard/usda-census-of-agriculture-for-american-indian-reservations/). The top 10 US states in numbers of dairy cows that calved represent 75% of the total US herd, with geographic concentrations of dairy cows in California, the Great Lakes region, Pacific Northwest, and Texas (Table 1). In addition to the beef and dairy cows on US grazing lands, the report has 5.61 and 4.45 million replacement heifers, beef, and dairy, respectively, that would be grazing as well. Unknown is how many of the other heifers and steers above 500 pounds in weight (9.71 and 16.58 million head, respectively), may spend part of the year grazing on US grazing lands. Combining the other heifers and steers >500 pounds and the calves under 500 pounds, provides an estimate of the total non-replacement stockers that could be grazing at some point on US grazing lands at 40.2 million head. Sixty-eight percent of these stockers is found in the top 10 states, with the Great Plains again being the dominant geographic region (Table 1). The vast majority (99%) of calves are presently finished on corn (*Zea mays* L.) and corn by-products in confined feeding operations to increase the efficiency and quality of beef production (Hayek & Garrett, 2018), but climate change impacts to crop production could impact this segment of the production cycle by altering the temporal and spatial distribution of feedstuffs and their quality. The distribution of ruminants among states within and across years can be markedly altered by regional droughts (Countryman et al., 2016).

**TABLE 1** Top 10 US states for beef cows and milk cows that calved, non-replacement heifers, steers >227 kg (500 pounds), and all calves <227 kg (500 pounds) (January 1, 2022 USDA-NASS), and breeding sheep (January 1, 2020, USDA-NASS)

| Beef cows that calved | | Milk cows that calved | | Non-replacement heifers, steers, and all calves | | Breeding sheep | |
|---|---|---|---|---|---|---|---|
| Texas | 4,475,000 | California | 1,720,000 | Texas | 6,310,000 | Texas | 585,000 |
| Oklahoma | 2,131,000 | Wisconsin | 1,275,000 | Nebraska | 4,400,000 | California | 315,000 |
| Missouri | 1,941,000 | Idaho | 652,000 | Kansas | 4,375,000 | Wyoming | 265,000 |
| Nebraska | 1,832,000 | Texas | 625,000 | Oklahoma | 2,430,000 | Utah | 240,000 |
| South Dakota | 1,610,000 | New York | 620,000 | Iowa | 2,360,000 | Colorado | 195,000 |
| Kansas | 1,422,000 | Pennsylvania | 470,000 | California | 1,855,000 | South Dakota | 187,000 |
| Montana | 1,299,000 | Minnesota | 460,000 | Missouri | 1,580,000 | Montana | 171,000 |
| Kentucky | 966,000 | Michigan | 434,000 | Colorado | 1,515,000 | Idaho | 165,000 |
| North Dakota | 945,000 | New Mexico | 292,000 | South Dakota | 1,500,000 | Oregon | 115,000 |
| Iowa | 925,000 | Washington | 261,000 | Wisconsin | 1,150,000 | Iowa | 108,000 |

In addition to cattle, sheep and lambs are key ruminants grazing US grazing lands. January 1, 2020 inventory numbers from the USDA-NASS indicated a total of 5.2 million sheep and lambs, with breeding sheep inventory at 3.81 million head. The top 10 US states in numbers of breeding sheep represent 62% of the total US herd (Table 1). Goat and kids inventory totaled 2.66 million head with breeding goat inventory at 2.18 million head. Nearly 20% of the milk goats and kids are in Wisconsin with another 10% in California. The primary state for meat goats and kids is Texas (37%) with other individual states not exceeding 5% of the total population.

## 3 | CONCEPTUALIZING ADAPTATION TO CLIMATE CHANGE

Managers of US grazing lands are currently applying management strategies within the context of directional climate change (warming and increasing atmospheric carbon dioxide) and climatic variability (precipitation—amount and seasonality, temperature swings, etc.; Derner et al., 2018a; Joyce et al., 2013). Management acumen for adapting to directional climate change can be addressed through the high predictability of forecasted and observed increases in warming and atmospheric carbon dioxide as changes on the ground are occurring incrementally through time (Figure 2). This provides managers with an application of their experiential knowledge in an iterative process, that is, learning by doing with monitoring information feeding back to subsequent adaptive management via multiple loop learning (Fernández-Giménez et al., 2019). A research needs exists for identification of tipping points in ecosystem responses to warming and atmospheric carbon dioxide as this knowledge would be highly informative to managers in their long-term strategic planning and risk assessments.

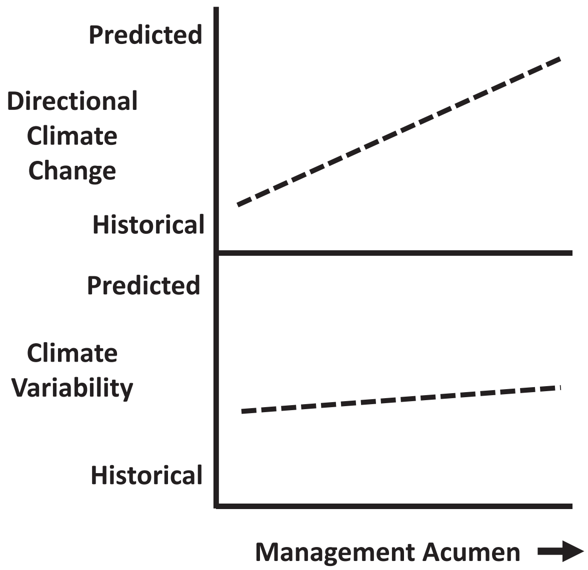


**FIGURE 2** Conceptual diagram of the hypothesized responses of management acumen of US grazing land managers to directional climate change (top) and climate variability (bottom).

In contrast to the directional climate changes, climatic variability is an area of considerable concern for grazing land managers and ruminant livestock (Polley et al., 2013; Reeves et al., 2013). A high degree of intra- and inter-annual climatic variability is an inherent feature of arid and semiarid grazing lands, with droughts and deluges potentially causing substantial land degradation and associated economic losses to managers (Coppock, 2011; Smith et al., 2007). The increasing frequency and magnitude of extreme events (i.e., droughts and deluges) can be problematic for many grazing land managers given the relative lack of experiential knowledge from prior similar events of the magnitude and duration predicted, and thus low management acumen to draw from (Figure 2). Contingency planning and preparedness of grazing land managers for these extreme events and their responses are crucial to minimizing negative effects on natural resources as well as the financial consequences for the production enterprise (Kachergis et al., 2014).

Practical considerations for adaptive strategies by managers of US grazing lands dealing with both the directional and increased variability aspects of a changing climate are dependent on decision making that integrates biophysical, social, and economic considerations (Nardone et al., 2010) in a social-ecological systems context. Adaptive strategies need to include knowledge that uptake by managers can be slow given managers' diverse adaptive capacity (Briske et al., 2015) and the divergence from local norms (i.e., business as usual), as well as the social and regulatory context of the ranch operation. Here, we separate these practical considerations for adaptive strategies into (1) directional climate change, and (2) increasing climatic variability. We understand that the intwining of direction climate change and increasing climatic variability is complex for grazing land management, but separation of the two here provides clarity and context for interpretation by grazing land managers. While several of the adaptive strategies are already being implemented to a degree by some grazing land managers in some systems, thereby providing natural opportunities for peer-to-peer learning, the extension of lessons learned and practical considerations for wider adoption merit discussion for implementation.

## 4 | DIRECTIONAL CLIMATE CHANGES

Impacts of directional climate changes are already influencing management of US grazing lands. Warming, changes to growing seasons, plant phenology, invasive species, and increased numbers of very hot days driving heat stress for livestock and people, are the current, primary challenges for managers. With increased atmospheric carbon dioxide, influences on plant production and quality (Augustine et al., 2018), and competitiveness of different plant species including invasives are of substantial concern. Species range shifts are occurring with both directional climate changes; key questions remain involving the magnitude and rate of these shifts. These shifts will have consequences to composition, function, and structure of grazing land ecosystems. The use of existing invasion risk assessment frameworks provides managers with the knowledge of potential impacts, and this provides opportunities to develop plans for limiting problematic species in their range shift, and enhancing those favorable species (Wallingford et al., 2020).

With the directionality of these climate changes, the incremental increases over time provide an opportunity for managers to experiment with adaptive strategies. The conceptual framework of Genetics × Environment × Management (Hatfield & Walthall, 2015) can help managers interpret the potential effects and outcomes of making changes to specific elements of grazing land management systems. For example, managers can select varieties of plant species that better match genetics to their environment for pastures, hayland, cover crops, and for restoration efforts involving native plant communities to adapt to increasing temperatures and reductions in forage quality with higher atmospheric carbon dioxide (Augustine et al., 2018). In addition, managers can alter ruminant genetics with substantial impacts to beef cattle (Garrick, 2011), shift the composition of livestock breeds to more heat tolerant ones or to different species (e.g., *Bos taurus* to *Bos indicus* for cattle) (Peinetti et al., 2011), or use heritage breeds like Criollo cattle (Anderson et al., 2015; Spiegal et al., 2020). These shifts provide opportunities to reimagine livestock production and associated provision of other ecosystem services from US grazing lands with higher temperatures.

Altering the environment can involve moving animals to different environments for part of the production chain to match animal demand to forage availability and quality resulting in optimizing resource efficiency and increasing provision of shade to reduce heat stress for livestock. With increasing temperatures and associated changes in the start of growing seasons and plant phenology, managers may alter the timing and use of plant communities in topographical gradients, largely in the western United States, by using higher elevation plant communities earlier than currently to place livestock in environments more suitable for reducing maintenance energy requirements and for enhancing grazing during higher plant quality periods. Also, managers may move livestock to different environments for a period in the production chain to adapt to the higher temperatures and changing quantity and quality of forages. Already a substantial number of stockers (post-weaned calves) are moved geographically across US grazing lands. Some examples of this include stockers grazing winter wheat (*Triticum* L.) in the Southern Plains, annual grasslands in California, and the western Great Plains rangelands (Roche et al., 2015; Thompson et al., 2019; Wilmer et al., 2018a). This movement of stockers may result in reductions in animal weight gains caused by mismatches in the rumen microbiome flora and the new plant communities, unfamiliarity with the environment, and associated differences in animal foraging behavior (Reynolds et al., unpublished data). A research gap exists here for assessing tradeoffs in climate and greenhouse gas (GHG) footprints associated with the long-distance movement of livestock across geographic areas. For managers wanting to adapt local environments, the use of natural (e.g., trees) or artificial shading (e.g., shade structures) can reduce heat loads for livestock and improve animal health.

Seasonal movement of livestock to match plant phenology, including moving livestock to higher elevation ranges, a transhumant practice of mobility, shares many characteristics with more extensive forms of pastoralism worldwide. In the western United States, Huntsinger et al. (2010) estimated that over 5000 ranches rely on government-owned summer range a part of their production cycle. As the authors note, ranchers tend to rely on montane summer ranges where much of their tenure is "shared, insecure, and declining" (Huntsinger et al., 2010). The scale of change on public lands grazing allotments was evaluated in an Idaho case study (Swette & Lambin, 2021), who found that forage consumed by livestock declined by 64% while 21% of grazing allotments were closed over a 90-year period. Loss of mobility strategies may reduce rancher's ability to match forage supply and demand as growing seasons extend and plant communities respond, while driving transformation to more sedentary, confined operational systems.

Managers could also modify management. For example, they may move livestock onto grazing lands during the night when lower temperatures occur to reduce heat stress (Islam et al., 2021). This would most likely be feasible with small-scale producers due to labor requirements and pasture sizes. Incorporating agrivoltaic systems, designed to mutually benefit solar energy and agricultural production, provides for dual use of land by managers with small ruminants (sheep and goats) to date. Lower forage production beneath solar panels was compensated by higher forage quality to result in similar sheep production compared to non-solar (open) pastures (Andrew et al., 2021), though logistical issues with designing agrivoltaic systems for use with cattle remain a research gap.

Increasing atmospheric carbon dioxide induces declines in forage digestibility and protein content (Augustine et al., 2018) that provides a need for adaptation strategies for modifying management of grazing lands. With "simple" plant communities (e.g., monocultures or a few species) and a largely agronomic focus for management, grazing land managers could consider strategic use of protein and energy supplements as well as incorporation of grazing cover crops within a typical use period of forages. Here the strategy could be to remove the standing crop of the forages via a haying event which provides stored feed for later use as well as moving plant phenology back to a more vegetative stage for regrowth. This strategy would be more advantageous in environments with higher seasonal predictiveness for reliable precipitation to promote regrowth of the forage. For more complex plant communities in rangeland ecosystems, increasing atmospheric carbon dioxide influences on advancing plant phenology and reducing forage quality will likely result in "summer slumps" where available forage has matured, and quality declined to result in a period of reduced animal performance. Grazing land managers could tactically use protein supplement during this period with diet quality monitoring informing decisions, and where possible given constraints of ranch-level control, chase green areas on the landscape to increase forage quality (Merkle et al., 2016). Low forage quality rangelands could be interseeded with nitrogen-fixing legumes to increase both production and quality, as well as carbon sequestration (Mortenson et al., 2004, 2005) though maintaining these highly preferred legumes in the plant community is difficult. Managers could also incorporate targeted grazing, prescribed burning including patch-burn grazing, and multispecies grazing to adaptively manage in concert with changing conditions and vegetation responses. They could also change the season of calving and/or grazing, change the season of pasture uses, and incorporate innovative hay/forage practices for storage of forage to reduce risk. If the rangeland production system is linked with some cropland, grazing summer cover crops during this "summer slump" period on rangelands would provide a forage source with improved quality. This could be achieved with precision livestock and rangeland management using virtual fencing to assist with matching forage availability and animal demand. Research gaps exist here involving novel uses of technology like virtual fence in real-world settings to provide management flexibility and achieve desired outcomes by managers.

With these directional climate changes, grazing land managers will need to assess their production efficiency and economic returns within a social-ecological systems context and into the future rather than just on a short-term a production basis (Ash et al., 2015; Herrero et al., 2013). Traditional approaches for assessing production efficiency have typically used metrics like production per unit female exposed, production per unit land area, and weaning weights. While these metrics have been highly useful for monitoring the production output, the efficiency of this production for operations is lacking. Alternatives for grazing land managers to consider include using metrics like production per unit atmospheric carbon dioxide equivalent, per unit methane emission, per unit GHG total emissions, or per unit nitrogen input. Use of these metrics provides the opportunities for grazing land managers to have baseline data for assessments of sustainability, climate-smart agriculture, and climate neutrality enterprises. This baseline data can be used by grazing land managers as a benchmark for continuous improvement in their operations. Research gaps exist here to inform these metrics and discover place-based solutions that can reduce GHG emission intensities. With changes to these systems-context efficiency metrics, the ability to have data-informed life cycle assessments (Rotz et al., 2019) increases the transparency to consumers and the public for grazing land managers.

## 5 | INCREASING CLIMATE VARIABILITY

Managers are also facing complex decision-making contexts due to increased climate variability. While much emphasis has been placed on development of robust drought contingency plans for grazing land managers through conservation planning efforts (Kachergis et al., 2014), management acumen for increasing climate variability is needed as experiential knowledge and lessons learned from prior events may have increasingly limited relevance (Figure 2). Along with swings in temperature, increased frequency, duration, and intensity of droughts, deluge precipitation events, changes in snowpack, changes in seasonality of runoff and greenup of vegetation, climate change-related weather variability creates less predictable management contexts, which leads to increased risk and uncertainty. Building substantial flexibility into grazing management plans and enterprise structure can help managers reduce risk to these forms of variability (Derner & Augustine, 2016; Torell et al., 2010). Flexibility comes in many forms, including mobility, storage, diversification, resource pooling, and market-based approaches.

Flexible stocking strategies—increasing or reducing ranch stocking rates with forage production trends within and across grazing seasons—have traditionally been eschewed by grazing land managers due to uncertainty of seasonal precipitation forecasts. However, establishment of regional grazing land production responses to precipitation using long-term forage and weather data (Petrie et al., 2018) provides predictive ability to flex stocking rates with yearlings to proactively match animal demand with forage availability (Derner & Hart, 2007). Moreover, the influence of sea surface temperature anomalies including the Pacific Decadal Oscillation and El Niño Southern Oscillation have signature pattern influences on the dynamics of grazing land productivity in grasslands of the Great Plains (Chen et al., 2017). When the Pacific Decadal Oscillation signal is warm, productivity in enhanced and variability of vegetation production is less. Conversely, when the Pacific Decadal Oscillation signal is cool, productivity is reduced, and variability is high. These climatic determinants influence livestock production as well (Derner et al., 2019; Raynor et al., 2020). Further, advances in remote sensing technology and big data analyses improve our ability to predict future variability in grazing land productivity (Gaffney et al., 2018; Kearney et al., 2022a; Podebradska et al., 2022) and quality (Irisarri et al., 2022). Satellite time series data have been used to predict spatial and temporal patterns of forage production and diet quality, as well as the resultant livestock performance in the Great Plains (Kearney et al., 2022b).

As weather becomes more variable, so do forage resources. Adaptive management that uses experimentation and data-derived decision making can help managers match animal demand more effectively with forage availability to achieve desired operation goals (Derner et al., 2021a). For example, the rapid advancement of predictive forecast tools like Grass-Cast that translate seasonal climate outlooks (Hartman et al., 2020; Peck et al., 2019) can assist grazing land managers with proactively using guides for flexible stocking rates (Raynor et al., 2020). Further, advances in remote sensing (Kearney et al., 2022a, 2022b) provide managers with the current vegetation conditions to alter the timing of grazing on landscape components, and use targeted grazing to reduce invasive plants and manage vegetation (Bailey et al., 2019; Marchetto et al., 2021). Managers can proactively plan for extreme precipitation events by incorporating soil health management practices that enhance infiltration and prevent runoff during deluges, as well as retaining soil water during drought periods (Bagnall et al., 2022; Derner et al., 2018b).

Across ranching communities, some ranchers may be better able to adapt than others. For example, adaptive capacity can be enhanced by a larger property size, topographical differences across the property, soil differences, and associated differences in plant communities (i.e., ecological sites, Reynolds et al., 2019). Experience in the industry can also impact adaptive capacity. Munden-Dixon et al. (2018) found that first-generation ranchers have fewer information sources and management strategies to deal with droughts, and are more susceptible to the impacts of drought than their multi-generational counterparts.

Larger ranchers or those with spatial separation of grazing lands in different parts of the same region, in different regions, and/or states provide land managers with flexibility to match animal demand to forage availability through movement in time and space, like livestock mobility across large landscapes in Australia for reducing risk to variability in forage production in space (McAllister, 2012; McAllister et al., 2006). However, trends in reduced access to public grazing resources in the western United States (Huntsinger et al., 2010; Lewin et al., 2019) and increased public pressure to remove cattle from public lands (Kauffman et al., 2022) are notable barriers to increased mobility and the adaptation afforded by these strategies. Grazing land cooperatives offer an opportunity to collectively take advantage of social learning networks (Bennett et al., 2021; Ghorbani & Azadi, 2021; Ooi et al., 2015), and potentially improve social and material support for adaptation greater than can be individually attained within a single property. Other examples of frameworks to inform flexible cooperative grazing groups include (1) public lands-based grazing associations, which are common on the US Forest Service National Grasslands, comprised of ranchers closely working with public lands agencies to manage federal grazing permits, (2) market-based agistment schemes (Reeson et al., 2008), and (3) efforts such as prescribed burn associations (Weir et al., 2016).

Integrated livestock–crop production systems, including the grazing of cover crops (Smart et al., 2021; Sulc & Franzluebbers, 2014) are an emergent adaptive management strategy. Integrated livestock–crop production systems can reduce enterprise risk, restore degraded land, increase productivity, and diversify production (Palmer, 2014). In addition, by integrating livestock with crops as well as with forests, manure from livestock can be used as fertilizer to improve soil nutrient status and soil organic matter (Sulc & Franzluebbers, 2014). Combining crops and livestock capitalizes on synergies among the ecosystem components by improving physical and chemical characteristics of soils which results in decreasing the need of new areas for increased production. Greater use of ruminant livestock to graze crop residues could provide additional synergies between crop and livestock production such as coupling of nutrient cycles to reduce the need for synthetic fertilizers. As the cost-effectiveness of technology like virtual fence increases (Anderson, 2007; Umstatter, 2011), these technologies may help reduce logistical issues with grazing ruminant livestock on croplands, including excluding animals from sensitive areas (Boyd et al., 2022). At the enterprise level, virtual fence and other technologies offer innovative opportunities to apply precision grazing and livestock management to US grazing lands (Bailey et al., 2021) by providing manager flexibility in location of livestock on the landscape for a period of time without constraints in current fence infrastructure that often delineates tracts of land (e.g., quarter sections and sections). Finally, agroforestry provides an adaptation strategy in many temperate grazing lands around the world (Lehmann et al., 2020; Palmer, 2014), but to date, adoption has been limited in US grazing lands (Romanova et al., 2022). However, a recent case study evaluating the practice of integrated sheep–vineyard systems in California documented high levels of adopter satisfaction with the practice and reduced input and labor costs relative to non-adopters (Ryschawy et al., 2021).

Numerous forms of storage and diversification can also help reduce risk to variable climate. Regarding enterprise structure, increased climatic variability may require greater use of stored forage (e.g., grass banks, hay supplies, Conservation Reserve Program lands), increased contingency planning, and the ability to alter herd sizes and production systems, all of which require capital investment (Didier & Brunson, 2004). Increasing hay production and subsequent storage is a drought adaptation strategy for pastoral systems in Africa (Kimaru et al., 2021). Forages on US grazing lands could be hayed when grazing management cannot keep the vegetation in a desirable vegetative state; this would be most practical for pastures or irrigated/sub-irrigated areas. For enterprise structure flexibility, shifting from a cow–calf enterprise only to mixed cow–calf with the addition of a yearling cattle (stockers) enterprise can be critical for economic success of the operation, especially in regions of highly variable forage production (Ritten et al., 2010; Torell et al., 2010). Managers will need to increase the proportion of yearlings in their operations as increasing climate variability occurs (Figure 3) for maintaining profitability as cow herd numbers at the individual ranch level reduce to minimize negative economic consequences of selling breeding stock during dry/drought periods (Hamilton et al., 2016). Cow–calf operators will need diversified adaptation strategies to offset negative economic impacts of climate change. Family operators can diversify their income and agroecological activities as telework, agro- or environmental tourism and other opportunities become more available

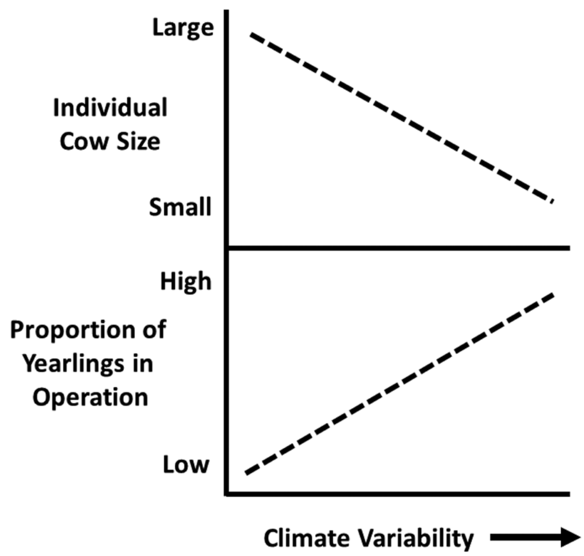


**FIGURE 3** Conceptual relationship between responses of individual cow size (top) and proportion of yearlings in an operation (bottom) in response to increasing climate variability on US grazing lands.

to different family and community members (Sayre et al., 2012). This can build agriculture's capacity for creative, collaborative adaptation strategies. Maintaining profitability of individual ranch production operations is paramount to the economic sustainability of rural communities with a changing climate (Derner et al., 2018a).

Greater enterprise flexibility would allow grazing land managers to sustain desired cow herd genetics and to maintain a stable, albeit smaller, number of breeding cows, by eliminating the need to liquidate cows during drought and restock following drought. However, this can impose additional costs and financial risks, especially for managers that are naïve with yearling enterprises, that may be unattractive to some managers (Torell et al., 2010). Additionally, with a smaller cow herd, there will be fewer calves to enter the stocker (yearling) phase of cattle production. Adaptive strategies for grazing land managers should emphasize matching cow size and environment for sustainable production (Beck et al., 2017), as large cow sizes substantially increase feed costs. Optimum beef cow weight for economic annual returns in the Southern Plains was 432 kg (Bir et al., 2018), and 453 kg cows were the most efficient in semiarid rangelands (Scasta et al., 2015). Research gaps exist here regarding the knowledge of cow size to GHG emission intensities in different environments. As the variability in climate increases, managers should reduce cow size to reduce risk, feed input costs during periods of low forage availability, and cow numbers as a proportion of total animals in the operation should decrease as well (Figure 3). Grazing land managers can also incorporate market-driven flexibility in their grazing management decisions to increase economic returns (Baldwin et al., 2022).

## 6 | SOCIAL CONTEXTS FOR ADAPTATION

Our emphasis in this review is on the ranch operation scale and we pay specific attention to directional climate changes and increased climate variability. We recognize that there are many social, political, and economic factors shaping the ability of managers and agricultural communities to employ adaptation strategies to these and other climate-related dynamics, and that in these sociological and political ecological contexts it is not appropriate to examine practice adoption solely as an individual, psychological, or moral problem (Sayre, 2004). As Green et al. (2022) documented via focus groups with ranching communities around the western United States, grazing land managers may feel limited amounts of agency (control) to adapt to multiple scales and types of social and ecological change that intersect in these agroecosystems. For example, land ownership patterns in the Intermountain West have shifted because of larger-scale (global) economic and cultural dynamics. While publicly managed grazing lands have had a role in sustaining lower income communities, trends in high net worth landownership of ranching lands (Epstein et al., 2022) are shifting grazing land geographies. This land ownership change not only reshapes specific patterns of grazing land resources, but also manager goals across the landscape related to wildlife, public access, and ranching community cultures, with real consequences for ecosystem management and climate adaptation practice adoption that merit additional research and dialogue (Epstein et al., 2019).

As a second example of how climate adaptation is a broader social and administrative issue and not just a problem of behavior or knowledge of an individual manager, mangers and ranchers frequently cite consequential administrative, logistical, and bureaucratic barriers to implementing flexible grazing management or drought adaptation practices on federal grazing lands. In these cases, creating opportunities for managers to employ adaptive practices on the ground may require long-term commitment to collaborative efforts, policy changes, or research-based approaches to change making with partners such as federal agencies, ranchers, conservation groups, and researchers working over large, complex landscapes (Sayre et al., 2012). Examples include the Collaborative Adaptive Rangeland Management project (Augustine et al., 2020; Derner et al., 2021b; Wilmer et al., 2018b), the Bureau of Land Management's "Outcomes-Based Grazing" program (https://www.partnersinthesage.com/outcome-based-grazing), and work to collaborate on adaptive triggers for drought management on Arizona's Tonto National Forest (Brugger et al., 2018).

Marking grazing lands as social-ecological systems provides an opportunity to see interconnections among subsystems in agroecosystems that shape and constrain climate adaptation. For example, a growing body of research is looking at what makes these collaborative approaches successful, with a recognition that social, ecological, conservation, and climate adaptation goals on grazing lands are interconnected and interdependent (Brunson & Huntsinger, 2008; Epstein et al., 2021). Along with this, there is growing recognition of managers' local ecological knowledge and long-term management time frames, as well as increased engagement with Native Science and Traditional Ecological Knowledge (Elk, 2016) to understand rangeland management. However, the capacity of land managers to replicate and practice these forms of knowledge is increasingly challenged (Aswani et al., 2018; Sharifian et al., 2022). Additionally, operational change is often incremental over a rancher's lifetime as they navigate technological, economic, and family dynamics and some ranch cultures may hold the norm that one generation should not impose their will on the decision making of another (Wilmer & Fernández-Giménez, 2015). Thus, the capacity or interest of ranchers to plan for transformative change or for multiple future generations is constrained not just by knowledge, but by governance frameworks, social norms, and economic structures.

## 7 | CONCLUSION

In this paper we have outlined practical considerations for grazing land adaptations to climate change, should have specific attention to directional climate changes and increased climate variability. The overall themes of these adaptive tools are flexibility and learning under uncertainty. We recognize that operations with greater land, social, or other capital resources may be better able to adopt flexible strategies. Managers may rely on conservation or farm policy programs or market-based approaches for flexibility and risk reduction, while in other cases they may draw from their social capital and strategic collaborations to bolster adaptive capacity across landscapes and time. We offer general conceptual frameworks (Figures 2 and 3) for the challenges and processes of adaptation that indicate growing complexity for managers as climate and ecological dynamics diverge from historical baselines and the realm of manager's experiential knowledge. These simplified frameworks can help frame conversations, future research, and new imaginative solutions among researchers, managers, and communities about systems-scale knowledge needs and adaptation to address increasingly uncertain and complex change at multiple scales. While the complexity of social, political, and ecological dynamics in these systems is posing new challenges for grazing land managers, it is important for decision makers to remember their support networks can now be bigger than ever and information is widely accessible even in very remote areas. Ranchers, farmers, and land managers have access to new, tele-connected knowledge and peer-support networks, collaborative efforts are becoming more mainstream. Climate and grazing researchers are developing new ways to improve the applicability of their research to the real-world context through collaborative or "co-produced" research efforts (Bestelmeyer et al., 2019; Derner et al., 2021b; Fernández-Giménez et al., 2019) that address new technologies and tools for adoption, communities of practice, and learning opportunities.

## AUTHOR CONTRIBUTIONS

**Justin D. Derner**: Conceptualization; writing–original draft; writing–review and editing. **Hailey Wilmer**: Writing–original draft; writing–review and editing. **Kim Stackhouse-Lawson**: Writing–original draft; writing–review and editing. **Sara Place**: Writing–original draft, writing–review and editing. **Mark Boggess**: Writing–original draft; writing–review and editing.

## CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

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