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Review

Managing risks related to climate variability in rangeland-based livestock production: What producer driven strategies are shared and prevalent across diverse dryland geographies?

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ABSTRACT

Rangeland-based livestock production (RBLP) primarily occurs in drylands where interannual variation in rainfall directly and indirectly affects economies, plant primary productivity (forage production), and livestock reproduction and mortality. Tight ecological and economic links to climate variation constrain production in dryland systems, but producers have a breadth of strategies to reduce climate-related risks and maintain RBLP. Research on these strategies has focused on context-specific tactics linked to specific systems and/or geographies. Inspired by studies that look for broader patterns to offer frameworks for discourse and to advance collective knowledge, we review global literature to identify risk management strategies related to climate variability that are in widespread use across dryland rangeland systems and geographies. We organize strategies within three key decision areas for producers engaged in RBLP: profit and return options, land use, and herd management. Across the decision areas, four strategies emerge as playing a strong role in risk management across the globe, with refinements based on local conditions. These shared and prevalent producer driven strategies are dynamic management of forage supply (in the decision area of land use), dynamic management of animal demand (in the area of herd management), and diversification and use of social networks (both of which apply across all three decision areas). Within each of the decision areas, we found diversification reduces climate related risks but has circumstances under which it is less effective; for example, large landholders already buffered to risk via landscape diversity benefit less from livelihood diversification. In practice, implementation of the four strategies often results in livestock producers who do not maximize short-term profits but instead prioritize land resilience, large herd sizes, lifestyle goals, and longer-term economic sustainability. In this synthesis, we considered existing producer strategies for reducing risk related to climate related variability – an intrinsic and defining characteristic of dryland rangelands – in order to highlight valuable areas in which research can support problem solving across diverse RBLP geographies and economies, especially in a changing climate.

1. Climate variability and risk in dryland rangelands

Managed grazing land covers more than 25% of the global surface area (Asner et al., 2004). Rangelands include a diverse set of biomes, such as grasslands, savannas, shrublands, deserts, steppes, tundras, and forests (Allen et al., 2011; Phelps and Kaplan, 2017). Drylands cover most of the area, supporting 78% the global grazing area in the early 2000s (Asner et al., 2004). Drylands can be characterized by an aridity index (the ratio of average annual precipitation and total annual potential evapotranspiration); the UN uses an index threshold of 0.65 or less to define a dryland (United Nations Environmental Management Group, 2011). While annual rainfall averages define drylands systems, these systems also tend to have high variability in inter-annual rainfall. Drylands are highly climate-variable because inter-annual variation in precipitation increases with reduced average rainfall levels (Knapp and Smith, 2001 Fig. 4b; Golodets et al., 2013).

Low and highly variable rainfall patterns create relatively high-risk conditions for rangeland based livestock production (RBLP). While mean climate conditions are strong drivers of management decisions and outcomes, effects of management decisions are even more complex

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and possibly more important within the context of climate variability. Climate variability affects forage production, livestock survival and fecundity, and disease and pest prevalence and virulence, as well as market volatility, access to markets, and effects of policies related to livestock production (Cossins and Upton, 1988; Lauenroth and Sala, 1992; Garrett et al., 2013; Kachergis et al., 2014).

Risks for RBLP are directly and indirectly linked to climate variability with immediate impacts (e.g., fire, flooding, disease or pest outbreaks, heat waves, blizzards, and drought) and also slower-paced hazards such as lags in forage dynamics, land degradation (e.g., erosion), and economic insecurity (leading to bankruptcy or market collapse) (e.g., Thurow and Taylor, 1999; Galvin et al., 2001; Sala et al., 2012). Adapting to risk ultimately means decreasing failures within components of livestock systems that impact profits or other returns. Because climate variability is inherent in dryland rangelands, numerous studies have investigated (both directly and indirectly) how producers manage for risks related to climate variability; however, most studies have focused on specific systems with limited ranges of economic development (e.g., developed or developing economy) or geographical area (e.g., Kenya or Wyoming), and may work through a single lens (e.g., socioeconomics, ecology). Research that compares and contrasts results across economies, geographies, and lenses of inquiry is necessary in order to offer frameworks that improve research efficiency and advance policy conversations. Notably, common ecological and social factors that define the possibilities and limits for production in arid and semi-arid landscapes (referred to 'drylands syndrome') have been synthesized to offer a set of principles that, when used by individual case studies, provide a framework for a broader reflections (Reynolds et al., 2007). Here we build on inspiration from previous work (such as 'drylands syndrome', outlining limits for production) to investigate producer management strategies. We undertake a qualitative review to answer the question: across geographies, what livestock producer management strategies are shared and prevalent for reducing risks related to climate variability in dryland systems? Our goal is to develop a framework that can advance collective knowledge. A framework for understanding long standing management strategies for addressing climate variability will provide insight into addressing climate change (IPCC, 2013).

2. Approach

Globally, RBLP systems vary widely in terms of access to resources and capital, institutional processes and organizational structures, cultural norms, and other factors that can enable or limit choices. Our overarching goal was to review the literature from these widely varying livestock production systems and identify shared (spanning variation in geographies) and prevalent (they are often found) management strategies that mitigate risks associated with high climate variability. A full analysis of factors that enable or limit management choices within and across diverse RBLP systems is not in our scope, but would be a next step in testing our framework and investigating the causes and consequences of specific management practices that operate within the broader strategy categories supported in this review. Our scope is also limited to past climate variability, though we recognize that climate change is expected to continue to increase the frequency and intensity of seasonal climate variability in many areas.

Due to wide variation in effect sizes that depend on initial conditions, extent of climate deviance, and multiple risk management practices that may be in play, we took a qualitative approach to the review. Qualitative approaches to discover and refine hypotheses have been encouraged as an important complement to quantitative studies in understanding rangeland management because they can capture factors that have eluded quantitative work and offer unanticipated results (Sayre, 2004). We used the 'soft systems methodology' (SSM), which was developed to address complex human affairs, often management (Checkland, 2000). 'Systems' refers to the process of inquiry, or a learning system

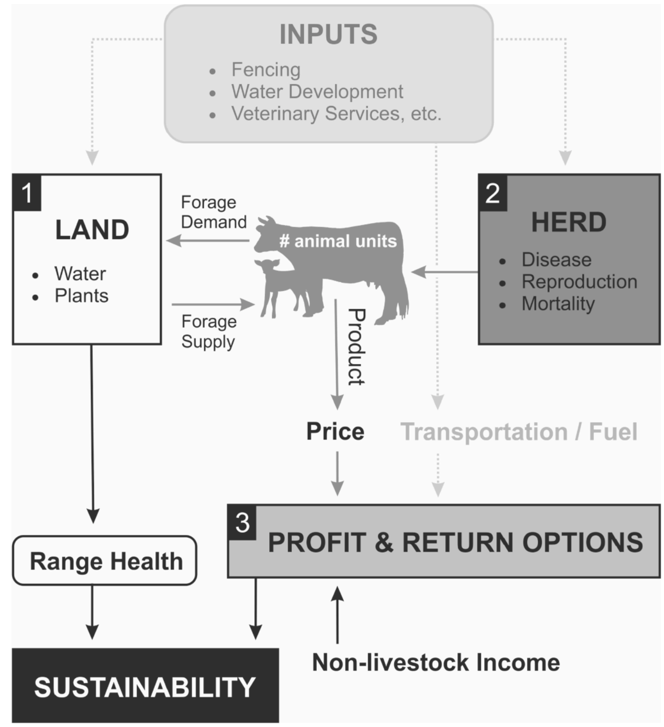

Fig. 1. Components of rangeland based livestock production and their relationships. Decision areas of 1) land use, 2) herd management, and 3) profit and return options are addressed in this paper. Arrows show the relationships among components.

(Checkland, 2000). We use a 'sense-making' approach to SSM to make sense of a complex situation, rather than the other option of an 'action-oriented' approach to figure out how to create a sought after change (e.g., among a diverse group of stakeholders, Reed et al., 2009). While constitutive rules for SSM vary with goals and experience using the method, we were guided by points outlined in Checkland (2000) highlighting that the process of inquiry is necessarily cyclical and iterative and activity models are a critical element. Inquiry was guided by three main steps (Checkland, 2000): 1) state the problem and find out about the problem situation to gain an initial appreciation; 2) formulate relevant purposeful activity models that are relevant to the problem situation; 3) explore the situation using the models to see if there are common trends.

For the problem statement (step 1) we focused on the perspective of the producer and asked: how do livestock producers in drylands manage to reduce risks related to climate variability across diverse geographies? For step 2, we identified three decision areas the producers must consider as the activity models most relevant to the problem situation. The three decision areas we identified are: land, herd, and profit and return (Fig. 1), which span RBLP in drylands across diverse geographies. The decision areas are interrelated, and a climate variability influence on one component may affect others (as shown in Fig. 1). We then used an iterative approach to (step 3) explore the situation through the literature to see if there are common trends in the three decision areas (land, herd, and profit). Due to the complexity of human systems, we explored a broad range of literature to consider patterns that may have been outside the immediate scope or perspective of the authors. For example, for livelihood diversification, the literature clearly identified climate variability as a driver of livelihood diversification in less affluent systems. This led us to explore livelihood diversification in more affluent areas, reasoning that even if climate variability was not always the factor directly considered in a study, climate variability is a key characteristic of dryland rangelands and therefore an indirect factor. Unlike empirical experiments, SSM cannot be strictly replicated but results of

Table 1
Shared strategies and the scope of activities found for each of the main decision areas of rangeland based livestock production decision making for managing climate variability.

Main areas of RBLP producer decision making	Scope of prevalent strategies, but not necessarily shared	Prevalent strategies that are also shared across geographies
Profit and return	Prioritizing lifestyle goals Specialization	Livelihood diversification[a] Social networks and social capital as financial buffers[a]
Land use	Cooperative management Fire Match forage demand with forage supply Pasture improvement Supplemental feed Agistment/leasing	Dynamic forage management[b] Resource base diversification[a] Social networks to support dynamic resource use[a]
Herd management	Selection of genetics Selection of species Large herd size Moderate stocking rate Agistment/leasing Herd mobility Market timing	Dynamic management of animal demand[b] Adjust stocking rates Herd diversification[a] Social networks to support mobility and stocking rate adjustments[a]

[a] Social networks and diversification are shared prevalent strategies among the main components of decision making and can be strong modifiers of the other prevalent strategies.

[b] Matching forage demand to forage supply is often achieved by similar strategies, with only slightly different emphases between land and herd decision areas.

SSM are 'recoverable' (Checkland and Holwell, 1998). Moreover, the review intentionally allows for debate and, as needed, improved frameworks to follow.

Due to the qualitative nature of the soft systems approach, it is important to explicitly present frameworks and concepts that informed our analysis of existing literature. In this case, our thinking about what constitutes a strategy to reduce risks related to climate variability was informed by existing theoretical frameworks including resilience, social-ecological systems, and livelihood analysis in rangelands. Resilience is the amount of change, in the form of a stress, that a system can buffer without altering its fundamental structure and function (e.g., Berkes et al., 2003). A socio-ecological system includes feedback loops of humans, ecological components, and their interactions (e.g., Gallopín, 2006; Cote and Nightingale, 2012). Resilience is determined by the capacities of a system to both proactively and reactively address a stress event or shock (Smithers and Smit, 1997; Gallopín, 2006); therefore, systems that are more resilient are better able to prepare for, respond to, and/or recover from a stress. Because change is thought to be pervasive and intrinsic to most systems, resilience may be strengthened when change is accepted and expected rather than controlled (Berkes et al., 2003). This may be especially important in the absence of feasible options for directly limiting the stress, and when the change is recurring rather than novel, as is the case for climate variability in rangelands (e.g., it is not feasible to irrigate to control rainfall variability, and rainfall variability is recurring rather than new).

Existing literature on resilience of socio-ecological systems and livelihood frameworks tends to focus on either developed or developing economies, with an emphasis on and origin from the latter, and few studies span diverse geographies. Here, we consider the producer perspective to identify producer strategies that span geographies and may therefore represent general features of the socio-ecological system dynamics associated with rangeland-based livestock production in drylands. In order to synthesize across geographies, we use the term 'producer' to refer to all RBLP livestock owners, 'pastoralist' to refer to producers operating in relatively more marginal, low cash economies, and 'rancher' to refer to producers operating in more affluent economies. We recognize that these definitions do not fit in all contexts (e.g., in Australia, producers who are not operating in a low cash economy may be identified as pastoralists), but we use them here for lack of more universal terminology. We also use the term 'sustainable' to refer to ability to maintain or improve livelihood over long timeframes. Our results are organized by decision area, with subheadings that largely reflect the shared and prevalent strategies, and results are summarized in Table 1. Results are intended to provide an international synthesis and perspective for scientists, policy makers, and producers. The synthesis helps in understanding existing and long standing producer strategies for addressing climate related variability, which is an intrinsic and defining feature of dryland systems. An understanding of existing strategies provides an important foundation for other studies focused on options for adapting to a changing climate.

3. Decision areas

3.1. Decision area 1: profit and return options

For rangeland systems and cultures, returns are determined by both monetary and non-monetary values and costs. Monetary earnings and costs include the value of sales and input costs such as labor (Fig. 1). In contrast, prestige in the community, status in social institutions (Davies and Bennett, 2007 - the Afar region of Ethiopia), and a range of uses for livestock, such as financial insurance or capital (Kinsey et al., 1998 - Zimbabwe, Thornton et al., 2007 - Kenya, South Africa, Tanzania), stock to pay dowries (Megersa et al., 2014 - Ethiopia), supply of milk, hides and manure, and draft power, can constitute high value returns that are difficult to translate into monetary or other numeric terms, making them formidable to model (Thornton et al., 2007). RBLP profits and returns operate over a range of temporal and spatial scales and typify the tightly-coupled human-environment systems that have developed in climate-variable drylands (Reynolds et al., 2007 - global).

3.1.1. Social networks and social capital

Non-monetary costs and values are often an important part of risk reduction and act to sustain returns over the long term. In some cases, an investment in social capital may give producers access to resources that buffer severe conditions, although the investment may come at a cost of monetary profit (Quaas et al., 2007 - Namibia). Integrated networks of indebtedness are central to managing risk (Fernández-Giménez and Le Febre, 2006 - global pastoral systems) and provide a safety net that allows producers to survive drought and also rebuild afterwards (Scoones, 1992 - southern Zimbabwe, Moritz et al., 2011 - global). Such a strategy allows pastoralists to live in some of the world's most marginal and unpredictable environments (Davies and Bennett, 2007 - the Afar region of Ethiopia, Starr, 1987 - central Niger). Social capital is also prevalent and important for RBLP in more affluent economies (Ellickson, 1994 - Central Valley, California, USA, Galvin, 2008 - global, Ooi et al., 2015 - western Colorado USA, Wilmer and Fernández-Giménez et al., 2015 - Colorado, New Mexico, Arizona in USA) and is tied to learning networks and long-term community conservation efforts (Briske et al., 2015 - central and western USA). Ranchers with networks and trusted connections are more likely to have greater adaptive capacity (i.e., the ability to convert resources into a useful response to a challenge) to persist through climate extremes (Marshall, 2015 - northern Australia), and this is likely due to greater access to information and trust in that information. However, the need for these connections can decrease with increasing ranch size, which increases the resource base and within-ranch spatial variability (Dobes, 2012 - Australia, Kachergis et al., 2014 - central and western USA). Informal connections, such as information exchanges with other ranchers, are trusted sources and present information in the context of ranchers' motivations and lifestyle, which can support the spread of information from formal networks (Liffmann et al., 2000 - central valley, California, Kennedy and Brunson, 2007 - western central Colorado, USA).

3.1.2. Non-livestock income and livelihood diversification

Our review found that livelihood diversification is a contributing risk management strategy employed by many producers across diverse geographies to increase sustainability in the face of risks related to climate variability. Profits and returns from RBLP are often complemented by livelihood diversification including income and returns from other endeavors, such as off-ranch jobs in the local community, with substantial support in the literature from the U.S. (e.g., Smith and Martin, 1972 - Arizona, Brunson and Huntsinger, 2008 - western USA, Coppock, 2011 - Utah, USA), Australia (Wilkinson, 2007- NC Victoria and South Coast of Western Australia, Raymond and Brown, 2011 - Murray-Darling Basin), and Africa (e.g., Thornton et al., 2007 - Kenya, South Africa, Tanzania, Murungweni et al., 2014 - SE Zimbabwe, Ouma et al., 2012 - northern Kenya, Opiyo et al., 2015 - northern Kenya).

The role of livelihood diversification in buffering climate related risk, however, is influenced by land tenure, non-monetized returns, ranch size, and lifestyle goals. In less affluent regions, reducing risk to external forces may drive livelihood diversification (McCabe, 2003 - northern Tanzania, Thornton et al., 2007 - Kenya, South Africa, Tanzania, Opiyo et al., 2015 - northern Kenya). In African pastoral and commercial RBLP, diversification of livelihood options may improve household income less in wealthy households compared to poor ones (e.g, Thornton et al., 2007 for pastoralist and commercial households in Kenya, South Africa, Tanzania). However, the diversification process may inhibit economic growth that could be achieved with specialization (or, the converse of diversification; e.g, Pedersen and Benjaminsen, 2008), especially during periods of favorable climate. Diversification activities may include agriculture, wage labor in towns, making charcoal, beekeeping, and selling bush products (Liao et al., 2015 - Xinjiang, China, Opiyo et al., 2015 - northern Kenya). Cultivation is a common diversification option for RBLP producers in less affluent economies (Desta and Coppock, 2004 - southern Ethiopia, McCabe et al., 2010 - northern Tanzania, Zampaligré et al., 2014 - Burkina Faso; Opiyo et al., 2015). In some cases, however, it may reduce flexibility in future livelihood decisions, including reducing the ability of a producer to move more fully back into pastoralism in the future, due to relatively high income variability (Pacín and Oesterheld, 2014 - Argentina), a pull to become increasingly sedentary (to produce a good crop harvest), and a potential lack of assets to repurchase animals (Pedersen and Benjaminsen, 2008 - northern Mali). Successful livelihood diversification through cultivation is also dependent on labor availability (Berzborn, 2007 - NW South Africa).

Drivers for livelihood diversification are less clear in affluent areas, largely due to the types of questions being investigated in existing literature, but climate variability (see 1) is a likely direct or indirect driver of starting or maintaining the strategy. In the Western United States, livelihood diversification is common and has been reported for most survey respondents (Coppock and Birkenfeld, 1999 - Utah, USA, Liffmann et al., 2000 - central valley, California, Gentner and Tanaka, 2002 - western USA, Kachergis et al., 2014 - central and western USA). Similar results have been reported for Australia (Wilkinson, 2007 - NC Victoria and South Coast of Western Australia, Raymond and Brown, 2011 - Murray-Darling Basin). Livelihood diversification in developed economies includes both off-ranch incomes (e.g., wage and salary jobs) and other on-ranch resource use activities (e.g., hosting visitors for fee based hunting, agriculture), similar to less affluent regions, although the specific type of use varies. Livelihood diversification may be comparatively less effective in reducing risk when economies of scale can be utilized: large livestock holdings (Liao et al., 2015 - Xinjiang, China), increases in ranch size (Coppock and Birkenfeld, 1999; Kachergis et al., 2014 - central and western USA), and developed, reliable, and accessible markets (Tessema et al., 2014 - global, focus on Africa) may do more to reduce risk than livelihood diversification . These systems are complex, however, with many factors at play. Interestingly, the extent of livelihood diversification in the western U.S. may be increasing as land has become an investment for the affluent (Robbins, 1999 - western USA). This trend may reduce climate related risk although the risk is not the direct motivation. Land use in the western US has also been shifting in orientation from production (e.g., RBLP) to amenity based consumption (Walker, 2003 - western USA), which can increase income diversification if both are employed by individual producers. Consumption-oriented land-use expands the use of managed land to include businesses with hunting for fees (with impacts on how woody vegetation is managed, Hurst et al., 2017 - central Texas, USA), tourism around aesthetics and nature, energy development, and also selling land for real estate development.

In many cases, livelihood diversification may support longer-term risk reduction related to climate variability by allowing management choices that forgo short-term gains. A range of studies demonstrate that producers make decisions to prioritize lifestyle and socioeconomic goals over profit in both developed economies (Smith and Martin, 1972 - Arizona, USA, Grigsby, 1980; Brunson and Huntsinger, 2008 - western USA) and in less affluent economies (Thornton et al., 2007 - Kenya, South Africa, Tanzania, Ayantunde et al., 2011 - E and W Africa). When ranches occupy valuable real estate, for example, ranch owners accept suboptimal returns on their land and livestock investments by foregoing the opportunity of selling (Sayre, 2004 - USA). As the landscape becomes increasingly urban in character, however, some crucial elements of the ranching lifestyle may be compromised, RBLP may be restricted, and ranchers may sell with intentions to start elsewhere (Liffmann et al., 2000 - central valley, California). Furthermore, producers can make management decisions that are conservation-oriented (McCabe, 1990 - northern Kenya, Brunson and Huntsinger, 2008 - western USA, Wilmer and Fernández-Giménez, 2015 - Colorado, New Mexico, Arizona in USA), where stabilizing income over the long term is preferred to maximizing it in the short term (Torell et al., 1991 - eastern Colorado, Foran and Stafford Smith, 1991 - central Australia, O'Reagain et al., 2011 - northern Australia tropical savanna). Long-term income stabilization to support lifestyle goals may be a shared and prevalent management strategy that indirectly reduces risks of climate variability across geographies, but this hypothesis requires further research. One exception would include management of small hobby farms in developed economies that are moving away from conservation goals (Wilkinson, 2007 - NC Victoria and South Coast of Western Australia) as new technologies, market prices, and changes in demographics can weaken the feedback loops that make sustainable management practicable (McAllister et al., 2006 - Australia).

3.2. Decision area 2: land use

3.2.1. Dynamic management of forage supply

Globally, producers in drylands attempt to reduce risk by making operational decisions in response to current or predicted forage availability, and we refer to this as 'dynamic forage management'. Rainfall is most often the strongest determinant of forage production (Irisarri et al., 2016 - North American semi-arid grasslands) and, especially on the drier end of the drylands spectrum, very different grazing intensities may have little impact on forage production relative to rainfall (Buitenwerf et al., 2011- semi-arid savanna region in eastern South Africa, Reid et al., 2014 - global). Livestock producers therefore often consider precipitation forecasts and predicted impacts of weather on forage supply when making management decisions. This is especially evident in RBLP systems heavily affected by more predictable patterns of precipitation variability such as the Southern oscillation (aka El Nino) in Australia (McKeon et al., 2009 - northern Australia, O'Reagain et al., 2011 - northern Australia tropical savanna, Pahl et al., 2016 - northern Australia), Africa (Thornton et al., 2007 - Kenya, South Africa, Tanzania), and South America (Valdivia et al., 2000 - Altiplano, Bolivia). However, to be used, forecasts must be perceived as reliable (Jochec et al., 2001 - west Texas, USA).

Producer attempts to dynamically manage forage are further complicated by weak cause and effect relationships between precipitation and forage, and feedback loops that may contain delays. While producers who make forage-related operational decisions based on current-year precipitation may substantially reduce risks compared to producers that do not adjust their management in response to weather, a longer-term view of system dynamics may be necessary to fully optimize operational profitability and sustainability. For example, global grassland models show that primary production (forage quantity) varies more among years than precipitation, and that the relationship between primary production and precipitation is weakly nonlinear; wet year forage production does not make up for dry year production (Hsu and Adler, 2014 - global grasslands). Carryover effects in production (or, delays in recovery of production) may, however, differ based on environmental context. In South Africa, 'good' grasslands (categorized by basal coverage and species composition) displayed production carryover effects of four years, while medium and poor grasslands recovered more quickly with carryover effects ranging from 1 to 35 months (Wiegand et al., 2004- semi-arid South African grassland). Contemporary adaptation and historical evolutionary processes may also impact vegetation responses to climate as well as grazing (Porensky et al., 2017 - shortgrass steppe in Colorado, USA).

In the face of these weak linkages between forage and climate, producers often attempt to manage proactively for sustained forage supply in a context of climate variability. Specific strategies to accomplish this goal are diverse, even within a given geographical realm (e.g., Wilmer et al., 2018 - western Great Plains,USA). Common and non-exclusive approaches include:

- conservative stocking rates, which enhance the probability that available forage will be adequate for any given year or season (Stafford Smith, 1992 - Australia, Holechek et al., 2004 - U.S. focused, Heitschmidt et al., 1990 - Texas, USA, and see 3.3.1)
- rotational approaches, which enable rest periods for forage to regrow, may enable achievement of wildlife objectives, and also allow managers to match grazing strategies with landscape diversity, see below (Fernández-Giménez et al., 2019 - eastern Colorado, USA; Sherren et al., 2012 - SE Australia, Teague and Barnes, 2017 - global, but see Briske et al., 2008 - global, with an emphasis on USA and South Africa)
- targeted grazing, which seeks to achieve specific vegetation management goals, such as invasive species reduction or fuel load management, via specified timing, duration, spatial distribution, and intensity of use (Frost and Launchbaugh, 2003 - USA, Davies et al., 2016 - shrubland in Oregon and Washington USA, Butz, 2009 - savanna in northern Tanzania)
- season-long rest or deferred rotation, which creates longer-term regrowth opportunities for forage and may help achieve wildlife objectives (Heitschmidt et al., 1990 - Texas, USA, Fernández-Giménez et al., 2019 - eastern Colorado, USA)
- grassbanking, or storage of forage in certain pastures or communally managed reserves (Gripne, 2005 - western USA, Fernández-Giménez and Le Febre, 2006- global pastoral systems, Mwilawa et al., 2008 - Tanzania, Kachergis et al., 2014 - central and western USA).
- purchasing supplemental feed (Scoones, 1992 - southern Zimbabwe, Kachergis et al., 2014 - central and western USA) or growing supplemental feed or fodder, often with limited irrigation (De Kock, 1980 - South Africa, Le Houérou, 2000 - West Asia and North Africa).

It may also be possible to manipulate the quality and preferred traits of rangeland species through active restoration (planting or interseeding) in order to decrease risk during drought. Producers in drought-affected areas may find that planting to increase the abundance of highly water use efficient plant species improves primary production in the face of drought (Koshi et al., 1982 - Texas, USA, Lelièvre et al., 2011 - Mediterranean Europe), however, aside from dedicated fodder and feed production, this practice appears to be largely hypothetical in most drylands.

In addition to the array of common, short-term strategies for dynamic forage management, producers often make decisions to avoid the crossing of forage production thresholds, with the goal of maintaining forage supply over the long-term. This strategy involves multi-generational planning horizons, land stewardship, and an "ethic of care" about land and forage (Wilmer et al., 2018 - western Great Plains, USA, Wilmer, 2016 - western Great Plains, USA, Gill, 2014 - central Australia). Results of management practices over decadal time frames can be difficult to study, largely because it is not trivial to parse out internal feedbacks (e.g., grazing intensities) versus external forcing (e.g., climate variability impacts on vegetation) over longer time frames (Briske et al., 2003 - global, Herrmann and Hutchinson, 2005 - global, Irisarri et al., 2016 - North American semi-arid grasslands). External forcing, such as that from regional precipitation patterns or episodic shocks, and the non-equilibrium nature of most rangelands systems (Reynolds et al., 2007 - global) complicates the relationships among climate, management, and forage availability. Both management decisions and external forcing in non-equilibrium systems can result in the crossing of thresholds that influence possible future forage trajectories, making it difficult to define the appropriate scale and to find a control for evaluating the impact of management decisions. Moreover, management decisions may take 4–7 years to exhibit benefits due to lags in livestock production (Foran and Stafford Smith, 1991, a simulation study on grazing intensities in central Australia) and as long as 30 years for full display (Porensky et al., 2017, using experimental data from 75 years of sustained stocking rate treatments in semi-arid rangelands of Colorado, USA).

In light of these complex interactions among land, management, and climate variability, conceptual models of system dynamics are important tools for the identification of key vegetation thresholds and tipping points. State and transition models are one such tool; they describe potential vegetation states, drivers of change among states, and ecological thresholds constraining the reversibility of vegetation change (Briske et al., 2005; Westoby et al., 1989 and others). State and transition models are being developed for ecosystems around the world (e.g., Wong et al., 2010 - Victoria, Australia) and underlie one of the world's largest formal land management frameworks (Twidwell et al., 2013 - USA). A global review of state and transition models suggests the formal use is limited but growing (Bestelmeyer et al., 2017 - Australia, Argentina, USA, Mongolia), and there is a need to incorporate producer knowledge and experience into the approach (Knapp et al., 2010 - global, Kakinuma et al., 2014 - Mongolia). Many dryland producers may not use a formal and explicit conceptual model of system dynamics, but producers typically use similar, informal approaches for dynamic management in which they evaluate the current vegetation state and adjust to reach desired outcomes. For example, flexibility, complemented by adaptive learning and guidance by long term goals, are identified as three key themes shaped by broader social and economic factors in the Great Plains of the U.S. (Wilmer et al., 2018 - western Great Plains, USA)

3.2.1.1. Fire as part of dynamic forage management. Producers in some systems use fire to manage vegetation and feed quality. Shrub encroachment into grasslands is a natural component of fire-prone systems, however shrubs are not desirable feed for many livestock species. Producers may suppress fire when grass biomass is not high enough to carry a shrub-killing fire, and then choose not to suppress fire when shrub reduction is a likely result (Janssen et al., 2000 - model of shrub grasslands). Fire is also used to manage forage quality (Harris and Covington, 1983 - ponderosa pine forest in Arizona, Butz, 2009 - savanna in northern Tanzania, Johansson et al., 2012 - montane heathland in Ethiopia), manage livestock distributions (Fuhlendorf et al., 2009 - Great Plains USA with global comparison), and control livestock disease (Butz, 2009; Johansson et al., 2012); the combination of grazing and fire can maintain rangelands that would otherwise be forested, as in southeastern South America (Bernardi et al., 2016 - SE

South America). Targeted grazing can also be used to create fire breaks and increase landscape heterogeneity through patchy fire, as reported for East Africa (Butz, 2009) and in the U.S. (Scasta et al., 2016).

Fuel availability for fire (both the amount of fuel as well as the timing of drying of biomass) is largely driven by the interaction between rainfall and management; in the case where fire has been universally suppressed and not used as a management tool, wildfire can lead to catastrophic reductions in forage availability and undermine rangeland health (Janssen et al., 2000 - model of shrub grasslands, Bond and Keeley, 2005 - global, Butz, 2009 - savanna in northern Tanzania, Johansson et al., 2012 - montane heathland in Ethiopia). For commercial producers, when fire is part of the managed ecosystem, delaying stocking rate adjustments to climate conditions (see 3.3.1) while managing with fire optimizes rangeland health (Janssen et al., 2004 - savanna rangeland model). Interactions between fire suppression policy, perception of increased climate variability, and land use changes have led east African pastoralists to stop using fire to manage forage quality (Butz, 2009). Although fire as a range management tool was historically both shared and prevalent, complex interactions among public perception, policies, and land use change (e.g., urban and crop development) suggest fire may currently function as a more specific management technique whose use is locally justified. We therefore subsume fire under the broader 'dynamic forage management' strategy that is prevalent and shared (Table 1).

3.2.2. Resource diversity within rangelands

When there is within-landscape diversity (i.e., heterogeneity), livestock densities and ecosystem functions may be more stable. For example, at the large-scale, features such as melting snow, patchy fire, and rainfall variability cause animals to use the landscape in a non-uniform manner (Fynn, 2012 - global), thereby resting parts of the landscape and helping to avoid undesirable shifts in species composition (e.g., Morris et al., 1992 - southern tall grassveld of Natal, South Africa, Briske et al., 2008 - global, with an emphasis on USA and South Africa); although we note there are many other factors, such as stocking rate, vegetation composition, herbivore species, and season and duration of use, that can interact with landscape patterns to drive shifts in species composition. As another example, livestock with access to separate wet season and dry season resources have increased animal survival and productivity in drought-prone systems (Illius and O'Connor, 2000 - model of semi-arid rangelands, Buttolph and Coppock, 2004 - Andes of Bolivia, Fynn, 2012). Access to trees gives producers the option of lopping branches to supplement livestock feed (as in Scoones, 1992 - southern Zimbabwe). Greater landscape diversity can also provide more opportunities for land-based, non-livestock income such as hunting and energy development (Kachergis et al., 2014 - central and western USA).

3.2.3. Social networks to support dynamic resource management

More broadly, dynamic resource management occurs on both individual and collective levels in RBLP systems. Community-based arrangements to reduce risk related to climate variability, such as merging and cooperatively managing grazing lands, are important for both common and privately owned land (e.g., Reid et al., 2014, in a review of rangelands more broadly, including drylands). While the nature of the sharing arrangement can vary greatly for common and privately owned land, familiar and accepted terms of agreement are core to successful management for both types of land tenure. Water sharing is a good example. On private land, landholders may engage in cost sharing for improving water resources, but participation may only be embraced when the terms of agreement are voluntary (Olenick et al., 2005 - Texas USA). On common land in Niger, complex but well established social rules supported sustainable sharing of traditional water sources until an increase in modern water sources (e.g., cement lined wells, bore holes) disrupted negotiation norms, resulting in decreased resource quality (Thébaud and Batterbury, 2001 - West African Sahel). Similarly, lack of community involvement in dams in dryland Uganda resulted in poor

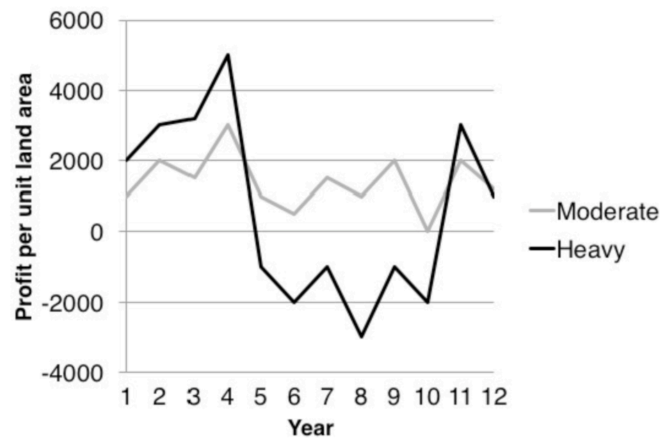

Fig. 2. Modelled profit per unit land area over 12 years in a precipitation-variable system subject to El Nino events (using data from O'Reagain et al., 2011): while a heavy stocking rate maximizes the potential for profit in any given year (e.g., years 1–4 and 11), managing risk with a moderate stocking rate doubles profits in the long-term.

maintenance and water quality (Mugerwa et al., 2014). The importance of accepted rules is emphasized in the contrast between open access and common property. When common property has recognized rules of management, overexploitation is unlikely. However, when arrangements are lacking and open access results in a drive for individuals to obtain as much as possible before others, overexploitation is predicted, suggesting the tragedy of the commons is actually the tragedy of open access (Bromley and Cernea, 1989 - focus on developing economies, Fratkin and Mearns, 2003 - northern Tanzania and Mongolia with broader reflections).

Social networks can also help producers gain access to enhanced resource diversity. Livestock sharing arrangements, such as agistment (e.g., producers manage by agreement to increase access to land), can serve to spread a herd over a broader area to reduce risk due to drought, are common in pastoral systems in Africa (e.g. Scoones, 1992 - southern Zimbabwe, Starr 1987 - central Niger), and are increasingly used in developed nations (Reeson et al., 2008 and McAllister, 2012 - northern Australia), making the strategy widespread (and see 3.3.2). Livestock sharing gives individual producers access to land unaffected by regional climate extremes, and increased land resource diversity buffers risk for producers. Social networks can serve as an alternative to capital intensive business models that invest in large landholdings in order to own spatial resource diversity, as included in the model used by S. Kidman & Co. (Dobes, 2012 - Australia).

3.3. Decision area 3: herd management

3.3.1. Dynamic management of animal demand

When precipitation is variable and livestock densities are unmanaged, model results show that increases in herd size lead to greater defoliation intensities in dry years compared to when rainfall is more constant (Illius and O'Connor, 2000 - model of semi-arid rangelands). Across dryland geographies, complex interactions among animal demand, climate variability and temporal scales, such as that example, result in risks that are further elaborated by socio-economic and market factors. In this section we outline that producers address these risks through dynamic management of animal demand and, while there are a number of management options that are well documented, stocking rate adjustment stands out as a shared and prevalent strategy.

Reducing herd size in response to drought can incur trade-offs related to short term profitability (Dunn et al., 2005 - northern Great Plains USA, Iglesias et al., 2016 - southern Spain, Fig. 1), sometimes emphasized by the potential for low market price due to widespread selling (O'Reagain et al., 2011 - northern Australia tropical savanna, Kachergis et al., 2014 - central and western U.S., Wilmer and Fernández-Giménez, 2015 - Colorado, New Mexico, Arizona in USA), or because of tax consequences (Dunn et al., 2005 - northern Great Plains, USA). With a longer term perspective (e.g., 10–15 years), however, empirical data and models have shown that ranchers that adjust stocking rate during the year tend to be more profitable than those that maintain maximum stocking rates in variable climates (as Foran and Stafford Smith, 1991 model in central Australia, with stock sold at first signs of droughts, Díaz-Solís et al., 2009 model in Coahuila Mexico using an annual adjustment based on precipitation, O'Reagain et al., 2011 simulate in northern Australia with stocking rates adjusted in May and November based on forage and/or forecast, and Oliva et al., 2012 suggest through animal sales by comparing two time periods in southern Patagonia). However, as illustrated by a simple example in Fig. 2, management grounded in moderate stocking rates, without dynamic annual management, can also be beneficial in the long run – heavier stocking can maximize profit potential in good years but managing risk with moderate or conservative stocking can increase profit in the long term (O'Reagain et al., 2011 for northern Australia, and also supported in Danckwerts and King, 1984 in South Africa, and summarized for southwestern deserts in the U.S. by Holechek et al., 1999; the definition of moderate or conservative stocking varies based on environmental and land use context). Thus, with a longer term perspective, there may be value in dynamic management based on a moderate strategy that constrains the magnitude of stocking rate adjustments, resulting in a management option that is logistically more feasible. For example, in an undiversified system, limiting herd reductions to 20% of the herd and expansions to 10% of the herd (for a given land area) produced more profitable operations in the long term than unconstrained stocking rate adjustments (Pahl et al., 2016, using a simulation of cattle production in northern Australia from 1890 to 2012 with stocking rates adjusted based on forage availability after summer growing season). When stocking rates are modified once a year after the growing season (as in Pahl et al., 2016), increasing stocking rates dramatically (e.g., more than 10%) in response to strong forage production could create a greater risk of forage production decline the following year (Hunt, 2008 - Australia). Modeling results, however, are of course dependent on assumptions and technical definitions. While there is strong support for adjusting stocking rates, the magnitude of fluctuation that is most beneficial varies with context (e.g., market price for selling and buying, timing of available information).

Dynamic management of animal demand is also supported as an important strategy for pastoralists. Many pastoralists employ an opportunistic strategy in response to inter-annual variations in climate in order to maximize output over time (Sandford, 1983 - developing country pastoral systems). Animal demand and feed supply are matched through a number of decision areas (Scoones and Graham, 1994 - Africa). For example, in order to reduce stocking rates during drought, pastoralists can increase the size of the foraging area (Ellis and Swift, 1988 - Africa, Nozières et al., 2011 - global, Opiyo et al., 2015 - northern Kenya) or decrease herd size through selling (Tessema et al., 2014 - global, focus on Africa). Selling animals during drought not only matches animal demand to available forage resources, but also provides income and food during hard times. Herd size (number of animals) may even be maintained when prices are high (Barrett et al., 2004 - northern Kenya and southern Ethiopia) in order to allow flexibility to sell when droughts occur (e.g., Oba and Lusigi, 1987 - African pastoral systems), since meat on the hoof represents an asset and insurance for non-banked pastoralists.

Producers also use dynamic management strategies of moving the herd to less-affected areas (although the size and stocking rate may not change). Reserves, or areas that are set aside either intentionally or due to extenuating factors such as threats of predation, disease, or attack, may be available (Fernández-Giménez and Le Febre, 2006 - global pastoral systems). When next year's weather is unknown, producers will make utilization decisions, such as how to distribute cattle across space, based on current range conditions (Blench and Marriage, 1999 - semi-arid Africa and SW Asia, Jochec et al., 2001 - west Wilmer and Fernández-Giménez, 2015 - Colorado, New Mexico, Arizona in USA). Operational herd decisions such as timing of reproduction, the marketing of livestock products, and proportion of yearlings can also be made for less vulnerability to drought (Valdivia et al., 2000 - Altiplano, Bolivia, Kachergis et al., 2014 - central and western USA Wilmer and Fernández-Giménez, 2015).

3.3.2. Social networks for dynamic herd management

Social networks provide access to agistment options and supplemental feed and water for most producers; their use is shared and prevalent. For example, livestock loan agreements with neighbors less affected by climate extremes are a common strategy (Scoones, 1992 reports loan agreements for herders to move cattle from a clay savanna, which require heavy rainfall infiltration for grass production, to a sandy savanna that was productive in southern Zimbabwe). In some cultures, transfers can benefit the receiver by providing food aid (e.g., milk) and benefit the loaner through strengthening social networks (Moritz, 2013 - Far North Region of Cameroon). See also 3.2.3 above, covering loans and agistment under the Decision Area of Land Use, since loan arrangements are used to dynamically manage both land and herds.

3.3.3. Herd genetics and livestock diversity

Herd genetics influences susceptibility to drought, mortality from heat stress, disease tolerance, stability of reproductive output, and effective forage utilization (Nozières et al., 2011 - global, Scasta et al., 2016). Survival, growth, and reproduction are enhanced by heterosis (Cundiff et al., 1992 - Nebraska, USA), indicating a direct benefit of within-breed genetic diversity to risk management. There is genetic variation within breeds for heat tolerance and increased ability to survive, grow, and reproduce when resources are few, but research in this area is concentrated in the tropics (Hoffmann, 2008 - global), which means that producers in other regions may need to experiment in order to optimize within- and across-breed genetics or to reap the benefits of a diversity of types of heat- and drought-tolerances within a single-species herd. Epigenetics such as maternal effects on calf forage use efficiency (weight gain divided by consumption) can also be leveraged for greater resilience (e.g., Underwood et al., 2010 - Montana and Wyoming, USA).

In addition to optimizing intraspecific genetics, epigenetics, and age distributions within herds such as *Bos taurus* (cattle), *Capra hircus* (goats) and *Ovis aries* (sheep), producers may choose to husband multiple livestock species (Valdivia et al., 2000 - Altiplano, Bolivia, Jochec et al., 2001 - west Texas, USA, Reeves et al., 2013 - Wyoming, USA), taking advantage of anatomical and diet preference differences to increase the production of their land. This approach of broadening the genetic base to include interspecific variation has the benefits of increased ability to control disease via rotating livestock species through pastures (Ware, 2014 - SE Australia, Butz, 2009 - savanna in northern Tanzania), and better weed suppression through more complete forage utilization (Popay and Field, 1996 - global). Donkeys, cattle, sheep, and camels all have different drought and disease tolerances as well as different water and forage requirements (Opiyo et al., 2015 - northern Kenya). Obstacles to acquiring additional livestock species include their costs: assets are required (Megersa et al., 2014 - Ethiopia, Pacín and Oesterheld, 2014 - Argentina, Liao et al., 2015 - Xinjiang, China) and labor needs may change drastically (Thébaud and Batterbury, 2001 - West African Sahel). Herd diversity is a risk buffering tool available to most producers; although shared, it is not prevalent, which may be a response to the profit tradeoff between diversity and specialization (see 3.1.2).

4. Shared and prevalent strategies across decision areas

Risk management for direct and indirect impacts of climate variability is crucial for dryland RBLP to minimize losses and increase the

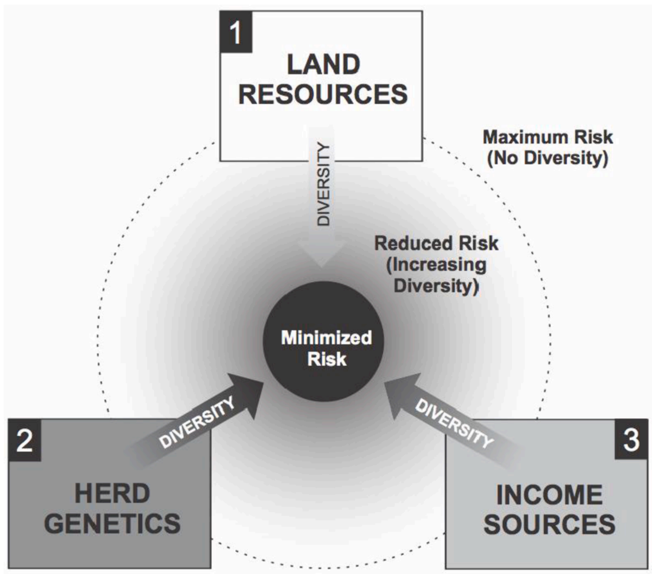

Fig. 3. Producers toolbox: increased diversity within the RBLP components of 1) land resources, 2) herd genetics, and 3) income sources generally reduces risks and increases sustainability.

likelihood of a sustainable operation. In this review we used soft systems methodology to work through three decision areas - profit and return options, land use, and herd management – and identify a set of shared and prevalent strategies for managing risk related to climate variability: dynamic management of forage supply, dynamic management of animal demand, diversification, use of social networks (Table 1). These strategies highlight similarities across diverse geographies that are often characterized by their differences, and represent a starting point for continued debate.

Our findings emphasize the point that decision areas are interdependent, in that management decisions focused on one area have impacts across decision areas (Fig. 1). For example, producers may prioritize lifestyle goals over profits, resulting in land use management choices that decrease risk to climate variability. Similarly, strategies to adjust forage demand (herd management) are closely linked with strategies to adjust forage supply (land use). We have identified that social networks affect multiple components of RBLP management, including stocking rate adjustments, access to supplemental forage and water, and perception of returns and risks. There are likely interactions between the pursuit of off-range income and access to social networks.

Several of the strategies we identified have also been emphasized in other work focused on more specific geographic or socioeconomic contexts. For example, Agrawal and Perrin (2008) identified mobility, storage, diversification, communal pooling and market exchange as key climate adaptation strategies for the rural poor. Similarly, Fernández-Giménez et al. (2012, 2015) explored the importance of social networks, mobility and storage for coping with climate variability in Mongolia. Focusing in the US on higher socioeconomic levels, Sayre et al. (2012) identified diversification as a key trait of ranch livelihoods, though this paper focuses less directly on climate risk. McAllister et al. (2009) provides a conceptual model outlining how variability in arid and semi-arid systems in Australia is managed by diversifying access to resources.

Our results build on the premise of the ‘drylands syndrome’ (Reynolds et al., 2007), which is determined by a combination of ecological, economic, and social factors that define the possibilities and limits for production in arid and semi-arid landscapes (Reynolds et al., 2007). The drylands syndrome offers a framework for advancing our knowledge across global drylands and proposes a set of features that are causally linked and, as such, should be considered together in management and policy (as supported in Australia by Stafford Smith et al., 2007 and Stafford Smith, 2008). Here, we worked within the broader dryland syndrome (specifically focusing on when ‘high variability’ relates to climate variability, and when the ‘human-environment system’ is RBLP). Similar to the principles of the drylands syndrome, the three interconnected decision areas and the shared and prevalent strategies outlined in this review can provide a framework for broader reflections and learning across geographies.

A recent review of the ‘drylands syndrome’ framework suggested that work in drylands yields idiosyncratic results and there is little that can be generalized, beyond the importance of local environmental knowledge (Stringer et al., 2017). In contrast, our review of the literature identified risk management strategies which are shared and pervasive across widely varying RLBP systems. Local knowledge and control are clearly crucial to sustainable RBLP (Reynolds et al., 2007), however, understanding shared adaptations in RBLP to climate variability across continents and economies can increase the capacity for empirical research to support problem solving at a global scale. Practices do not need to be prevalent (often found) to deserve further examination: once a practice is shared (spanning variation in geographies), we can begin to investigate mechanisms underlying success that are not limited to a single geography.

We find specific support in the literature that increased diversity within herds, income sources, and land resources (Fig. 3) all act to increase the sustainability of RBLP, which is not unexpected because diversity is a general mechanism for increasing stability and therefore sustainability (Box 1). Once one or two risk reduction strategies are in place, however, subsequent ones will likely have smaller effect sizes. We also find that often, reducing risks means decreasing the potential for maximizing profit in the short-term; however, dynamic management can buffer this impact since variability also means there can be highly profitable, opportunistic responses when conditions are favorable (e.g., Westoby et al., 1989 - global, Bastian et al., 2018- Wyoming, USA). One optimization approach is to embrace risks inherent in ecological and economic systems, resulting in a perspective that prioritizes options to increase predictability rather than options to escape threats (Foran and Stafford Smith, 1991 - central Australia, Scoones, 1992 - southern Zimbabwe, Thébaud and Batterbury, 2001 - West African Sahel). A version of this in which pastoralists attempt to increase reliability in the face of risk, rather than avoid risk, has been termed a ‘high reliability’ approach (Roe et al., 1998).

Complex interactions between external forces and management in drylands make sustainable RBLP technically demanding. The literature suggests management decisions to maintain sustainable RBLP are not intuitive (e.g., sometimes heavy grazing is constructive) and the advanced technological prowess of producers to manipulate stocking rates or densities in response to forage availability or predicted precipitation (dynamic management) is also key to sustainability. Modern analytical techniques borrowed from physics and engineering can be applied to assess the self-reliance of nested networks (or, overlapping decision areas) in RBLP and can be used to quantify net effects of diversity (Box 1) within- and across-networks and within their individual components (e.g., Girvan and Newman, 2002; Ahn et al., 2010). Network analysis has more recently been applied to dryland plant communities (Saiz et al., 2018 - global drylands) and this type of analytical technique can be used to quantitatively determine climate effects on livestock production and the relative influence of management and policy decisions within this variation. However, it is important for researchers working in these systems to understand that some important drivers of resilience in RBLP are difficult to quantify and/or are located off-range, specifically use of social networks and dependence on off-range income. Social networks, off-range income and their effects can be modelled using stakeholder analytic tools (Thornton et al., 2007 - Kenya, South Africa, Tanzania, Reed et al., 2009 - case studies from a range of systems), therefore sufficient models of RBLP sustainability will require extensive cross-disciplinary expertise.

Box 1

The diversity-stability relationship

The positive relationship between diversity and stability is a feature of many networks, including gaming (Jackson and van den Nouweland, 2005), wireless (Watteyne et al., 2009), molecular (Kitano, 2007), epidemiological (Poulin, 2010), economic (Pacín and Oesterheld, 2014), and ecological (Saiz et al., 2018) networks. This positive, although not necessarily linear, relationship has several overlapping explanations: 1) *redundancy* guards against failure, 2) *probabilistically*, larger arrays are most likely to contain individual members that confer stability, 3) each member of the *portfolio* has variable performance among years but in any given year at least one member will do well, and 4) stability *emerges* from interactions among members. In the redundancy and portfolio case, more diversity creates more function. In the probabilistic case, only some kinds of diversity create more stability. The emergent case could fall into either category: if emergent interactions are widespread, more diversity will tend to more stability; if localized, only some kinds of diversity create more stability.

5. Conclusion

Shared and prevalent strategies for producers to manage risk related to climate variability in dryland rangelands include dynamic management of forage supply; dynamic management of animal demand; diversification; and use of social networks, as supported by a qualitative review of three key decision areas - profits and returns, land, and herd. The shared and prevalent strategies highlight a valuable framework through which research can advance an understanding of RBLP across diverse geographies and economies. Working across geographies to compare and contrast similarities and differences within a common framework will offer efficiencies for policy making and the innovation of approaches to improve RBLP. This synthesis focused on existing producer strategies for addressing climate related variability, which is an intrinsic and defining feature of dryland systems. Understanding existing shared and prevalent strategies is important for other studies seeking to offer options for responding to a changing climate.

Conflicts of interest

The authors declare no conflicts of interest.

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